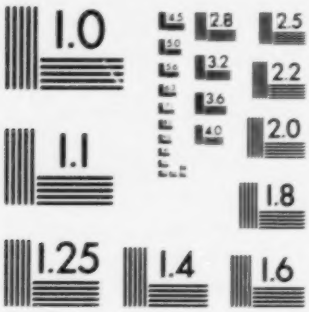
MS109

Micromedia Limited

The contents of this microfiche are copyright by the publisher of the original document. Please contact the original publisher for guidance in copyright matters.

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

This statement was filmed with this document. If the pages of the document are less clear than this statement it is due to the poor photographic quality of the document.

NATIONAL MICROGRAPHICS ASSOCIATION

24x

Site Characteristics and Landsliding in Forested and Clearcut Terrain, Queen Charlotte Islands, B.C.

Land Management Report NUMBER 64

JANUARY 1990

BC
Ministry of Forests

FISH/FORESTRY INTERACTION PROGRAM

This study was undertaken as part of the Fish/Forestry Interaction Program (FFIP), a multi-disciplinary research study initiated in 1981. The program was started following a series of major winter storms in 1978 that triggered landslides over much of the Queen Charlotte Islands forest land base. Originating on steep slopes, many slides deposited tonnes of debris in streams and on valley flats. The events raised private and public concerns over logging practices on the Islands and prompted the establishment of the 5-year program. Overall objectives of FFIP were:

- to study the extent and severity of mass wasting and to assess its impacts on fish habitat and forest sites.
- to investigate the feasibility of rehabilitating stream and forest sites damaged by landslides.
- to assess alternative silvicultural treatments for maintaining the improving slope stability.
- to investigate the feasibility and success of using alternative logging methods, including skylines and helicopters, and by logging planning to reduce logging-related failures.

The program is jointly funded by direct appropriations from the Canada Department of Fisheries and Oceans, the B.C. Ministry of Forests (Research Branch), and the B.C. Ministry of Environment (Fisheries Branch). Participating agencies include Forestry Canada (Pacific Forestry Centre), and the Forest Engineering Research Institute of Canada (FERIC), Vancouver, B.C.

Program results are published through the B.C. Ministry of Forests, Land Management Report series, as well as in papers presented at symposiums, conferences, and through technical journals.

For information about the program contact Ministry of Forests, Research Branch, 31 Bastion Square, Victoria, B.C. V8W 3E7.

90-03817/

Site Characteristics and Landsliding in Forested and Clearcut Terrain, Queen Charlotte Islands, B.C.

by
Kenneth M. Rood

K. Rood & Associates
3484 Oxford Street
Vancouver, B.C.
V5K 1N9

January 1990

BC
Ministry of Forests

Canadian Cataloguing in Publication Data

Rood, Kenneth M.
Site characteristics and landsliding in forested and clearcut terrain, Queen Charlotte Islands, B.C.

(Land management report, ISSN 0702-9861 ; no. 64)

Includes bibliographical references.
ISBN 0-7718-8900-3

1. Landslides - British Columbia - Queen Charlotte Islands. 2. Logging - Environmental aspects - British Columbia - Queen Charlotte Islands. 3. Cutover lands - British Columbia - Queen Charlotte Islands. 4. Forest site quality - British Columbia - Queen Charlotte Islands. I. British Columbia. Ministry of Forests. II. Title. III. Series.

QE599.C3R66 1989 551.3'53'0971112 C90-092006-8

© 1989 Province of British Columbia
Published by the
Research Branch
Ministry of Forests
31 Bastion Square
Victoria, B.C. V8W 3E7

Copies of this and other Ministry of Forests titles are available from Crown Publications Inc., 546 Yates Street, Victoria, B.C. V8W 1K8.

SUMMARY

This study examined the effect of site characteristics on landsliding rates for clearcut sites, clearcut areas, and forested drainage basins. A landslide inventory of 1337 forested and clearcut debris slides and debris flows was taken, along with measurements of watershed physiography for forested basins and a 100-m grid sample of clearcut site characteristics.

Slope dominated other factors in controlling landsliding, though for different reasons in open slope, gully headwall, and gully sidewall terrain. Open slope debris sliding was primarily controlled by the portion of the area exceeding 35°. This control was modified by slope shape and position. Gully headwall failure rates were also strongly related to average slope and the range of slopes. Slope shape and position exerted a strong influence suggesting the importance of moisture to these failures. Rates of gully sidewall failures, however, were independent of slope — not surprising in an environment where average slopes exceed typical internal angles of friction for non-cohesive soils.

Bedrock formation (Sutherland Brown 1968), physiographic region, and aspect (when adjusted for steepland area and slope differences) have no effect on landsliding.

The volume of material entering streams depends on the factors that produce debris slides and flows, as well as on the character of the terrain between the steepland initiation points and a stream. In forested drainage basins, both flows and slides provide material to streams. The volume entering streams is controlled by the frequency of gully failures and the proportion of steeplands along the basin. In clearcut areas, the situation is simpler: most of the volume is delivered by flows. The probability of stream entry is controlled by the gradient of the footslope between the bottom of clearcut steepland and the stream. Angles near 15° are critical: above this most flows enter; below, few do.

ACKNOWLEDGEMENTS

The assistance of the Department of Geography of the University of British Columbia is gratefully acknowledged. The department granted the use of its photogrammetric equipment for the initial landslide inventory as well as for the landscape sampling of clearcut areas. Dr. Michael Church of the Department of Geography kindly arranged computer time and data entry services for the analyses of the landslide inventory and the clearcut landscape sample.

I would also like to thank Western Forest Products, MacMillan Bloedel, Crown Forests, and the B.C. Ministry of Forests (Queen Charlotte City) for providing mapping of logged areas within their tree farm licences or jurisdictions. These maps were invaluable in the planning of clearcut investigations.

Dr. M. Church, Mr. J. Schwab (B.C. Ministry of Forests), Mr. C.P. Lewis (B.C. Ministry of Environment), and Mr. V. Poulin provided invaluable advice during the initial and subsequent organization of the study. I also thank Dr. Church, Mr. Schwab, and several anonymous reviewers of an initial draft of this report for their technical comments.

TABLE OF CONTENTS

SUMMARY iii

ACKNOWLEDGEMENTS iv

1 INTRODUCTION 1

1.1 Factors Controlling Slope Stability 1
1.2 Objectives of the Study 2

2 STUDY DESIGN AND METHODOLOGY 3

2.1 The Study Areas 3
2.2 Study Design 3
2.3 The Sample of Landslides 5
2.3.1 Landslide types 5
2.3.2 The landslide data set 6
2.3.3 Aerial photography 6
2.4 Landscape Description 6
2.4.1 Forested watershed physiography 6
2.4.2 Clearcut area physiography 7
2.4.3 Site characteristics of clearcut areas 7
2.5 Factors Confounding Analysis 8

3 LANDSLIDING IN FORESTED WATERSHEDS 8

3.1 Open Slope Debris Study 12
3.2 Gully Debris Sliding 12
3.3 Debris Flows 12
3.4 Landslides Entering Streams 12

4 THE SITE CHARACTERISTICS OF LANDSLIDES IN FORESTED TERRAIN 13

4.1 The Relation of Landslides to Site Characteristics 13
4.1.1 The volume distribution of landslides 13
4.1.2 Initiation site characteristics and debris slide magnitude 15
4.1.3 Initiation site characteristics and the number of landslides 17
4.1.4 Slope and landsliding 18
4.1.5 Aspect and landsliding 18
4.1.6 Slope shape, slope position and landsliding 18
4.1.7 Geology and landsliding 22

5 LANDSLIDING IN CLEARCUT AREAS 22

5.1 Landsliding and the Age of Clearcut Areas 24
5.2 Logging Roads, Landslides and Age 24
5.3 Landsliding from Open Slope Areas 26
5.4 Landsliding from Gully Headwalls 28
5.5 Landsliding from Gully Sidewalls 28
5.6 Debris Flows from Clearcut Areas 28
5.7 Landslides Entering Streams 31

6 SITE CHARACTERISTICS AND LANDSLIDING IN CLEARCUT TERRAIN 33

6.1 Landscape Position 33
6.2 Site Characteristics 33

7 CONCLUSIONS 38

7.1 Landslide Magnitude 38
7.2 Landsliding in Forested Terrain 38
7.3 Landsliding in Clearcut Terrain 38
7.3.1 Open slope debris sliding 38
7.3.2 Gully debris sliding 39
7.3.3 Debris flows 39
7.3.4 Site characteristics and landsliding 39
7.4 Implications for Prediction of Landsliding 40

8 REFERENCES 41

APPENDIX

1 Definition of variables used to describe landslides 43

TABLES

1 Primary features of the study basins, Queen Charlotte Islands 5

2 Significance levels for correlations between drainage area and other basin attributes 8

3 Weighted average physiography and sediment yield of basins in the Skidegate Plateau and Queen Charlotte Ranges 10

4 Relation of landsliding yield to average steepland slope 10

5 Functional slopes for the relation between landsliding yield and average steepland slope for different bedrock formations 10

6 Correlations of physiography and landslide frequency with the yield to streams 13

7 Kruskal-Wallis statistics for the relation between site characteristics and debris slide volumes 15

8 Acceptance or rejection of the null hypothesis for a relation between environmental variables and debris slide numbers 17

9 Description of the physiography and landsliding yields for different geological formations in the clearcut areas 22

10 The variation of average landsliding yields from roads, with age 24

11 Statistics of regression equations describing debris sliding and debris flows from steepland clearcut areas 26

12 Yield to streams and the angle between the clearcut area and the stream 31

13 Basic characteristics of open, gully headwall, and gully sidewall clearcut terrain 33

14 Chi-square statistics for the relation between site characteristics and the number of debris slides 35

Appendix 1

A.1 Description and classification of variables collected for each landslide from aerial photographs 45

FIGURES

1 Location of study basins on the Queen Charlotte Islands 4

2 The relationship of average basin slope, average steepland slope, and percent steeplands to forested basin area 9

3 The variation of landsliding yield with average steepland slope of the forested basins 11

4 The frequency and cumulative volume distribution of forested, clearcut, and road debris slides, Queen Charlotte Islands 14

5 The frequency and cumulative volume distribution of debris flows in forested and clearcut terrain, Queen Charlotte Islands 16

6 The volume, number and average size of open slope debris slides in forested and clearcut terrain over seven slope classes 19

7 The volume, number, and average size of gully debris slides in forested and clearcut terrain over seven slope classes 20

8 The distribution of open slope and gully debris slides over different aspects, slope types, and slope positions in forested terrain 21

9 The frequency of open slope and gully debris sliding over different geologic formations and elevations in forested terrain 23

10 Landslide volumes per area for clearcuts of different ages 25

11 The relationship between yield and average slope for the open slope portion of clearcut areas 27

12 Observed versus predicted debris slide volumes for the open slope portion of clearcut areas 27

13 The relationship between yield and average slope for the gully headwall portion of clearcut areas 29

14 Observed versus predicted slide volumes for the headwall portions of clearcut areas 29

15 The relationship between debris flow yield (m^3/ha) and the proportion of the clearcut area in gullies 30

16 The relationship between debris flow yield (m^3/ha) and the frequency of headwall failure 30

17 Average runout slope distributions for debris slides and debris flows 32

18 The variation of the frequency of debris sliding with slope in clearcut areas, Queen Charlotte Islands 34

19 The variation of the frequency of debris sliding with elevation and aspect in clearcut areas, Queen Charlotte Islands 36

20 The variation of the frequency of debris sliding with slope form, slope position, and bedrock formation 37

INTRODUCTION

Understanding the relationships linking landsliding to specific environmental conditions or terrain types can help foresters predict how clearcutting affects slope failure. One approach to predicting stability is to apply slope stability analyses to natural slopes. This is a complicated procedure, however, because of the high degree of variability of soil properties over space and time. Another approach is to compare the terrain characteristics of logged sites where failures have occurred to those characteristics on non-failed sites. In this way, factors that appear to most influence landsliding can be isolated (Rice and Pillsbury 1982; Rollerson and Sondheim 1985).

The approach used in this study differs again. Instead of sampling the landscape and noting the presence of landslides, the study identified the site and regional characteristics of a large number of failures and described the areal distribution of these characteristics within clearcut areas. The data do not distinguish between stable and non-stable sites, but rather describe the frequency and magnitude of landsliding associated with different site characteristics.

The occurrence or non-occurrence of a landslide is not the only aspect of landsliding pertinent to forest resource management. Also important are the total frequency of failure from a clearcut area, the magnitude or runout distances of the individual failures, and the proportion of landslides directly entering streams. These issues are examined in this report.

1.1 Factors Controlling Slope Stability

Slope stability analyses involve the limit equilibrium mechanics of slope stability. While these analyses require simplifying assumptions that are often not applicable on natural slopes, they do indicate the site characteristics likely to influence landsliding. For two-dimensional, planar failures of small, constant depth on infinite slopes, debris sliding or avalanching is predicted to occur when the available shear strength is less than the applied shear stress. A general factor of safety (FS) equation based on an infinite slope models (Sidle *et al.* 1985):

$$FS = S/\tau \qquad (1)$$

The applied shear stress (τ) is a result of the weight of trees, soil, and moisture on the slope and the slope angle. The shear strength (S), or the resistance to failure, is determined by the effective soil cohesion, the cohesion due to root systems, and a term including the difference between the total normal stress on the slope and the pore water pressure, and the angle of internal friction for the soil. Theoretically, when $FS < 1$, the slope is unstable and failure is imminent.

On natural slopes, the important factors affecting debris sliding or avalanching are: pore water pressures, which vary with storm patterns and local slope hydrology; soil characteristics; slope steepness; the depth to the potential failure surface; and in clearcut areas the removal of vegetative cover and subsequent deterioration of the root mat (Sidle *et al.* 1985). Other than slope steepness, all these parameters are difficult to measure in the field and vary greatly along and across natural slopes.

For a regional study of landsliding, it is impractical to measure directly any of these parameters other than slope steepness. It is assumed that the geologic, geomorphic, and physiographic properties of the landscape influence or even determine such local factors as the engineering properties of soils, chemical and mineralogical properties of soils, local site hydrology, and the influence of vegetation. If this is true, then relationships might be expected between shallow debris sliding and the local geology, geomorphology or physiography. This is the justification for the approach taken in this report.

Shallow landsliding is generally thought to be strongly slope dependent, with a threshold for initiation near 20° (Sidle *et al.* 1985). Studies from various regions indicate that above this threshold the probability of failure generally increases with gradient (Swanston 1974; Ballard and Willington 1975; Rollerson 1984). However, the relation of the probability of failure to slope may be only locally applicable, because of variations in geology, climate, and land use.

Bedrock geology appears to influence shallow, rapid landsliding of the soil mantle in several indirect ways (Sidle *et al.* 1985). Rock structure may be important to stability: downslope dipping structures may impede infiltration and provide potential failure planes; horizontal or upslope bedding may act to buttress the soil mantle and permit root penetration (Swanston 1974). Shallow soil mantles over massive and impermeable volcanic or igneous rocks may also be subject to failure. As well, bedrock may exert a secondary influence on surficial materials, and surficial geology may be important. Tills on the Queen Charlottes experience different landsliding rates and types than does colluvium (Alley and Thomson 1978).

In some areas, aspect may exert considerable control over the location of landslides where storm tracks are typically from one direction and exposed and lee slopes experience differing amounts of rainfall and wind stress on trees. Aspect may also reflect the distribution of steep slopes in areas where there is strong structural control of the landscape.

Slope shape in plan and profile controls landslide initiation through the dispersal and concentration of water in the soil. Generally, convex slopes are assumed to disperse water and be more stable than concave slopes which concentrate soil water into a few areas on the slope (Sidle *et al.* 1985). Debris sliding is often associated with gullies and depressions where groundwater flows concentrate and converge, resulting in higher pore water pressures.

1.2 Objectives of the Study

This study is part of the Physical Processes component of the Fish/Forestry Interaction Program (Poulin 1984), undertaken to investigate the influence of logging on mass wasting on the Queen Charlotte Islands and of effects of mass wasting on stream channels. Rood (1984) demonstrated the influence of logging on landsliding by comparing the rate of landsliding from clearcut and roaded terrain to long-term rates calculated for forested steeplands. This study employs the inventory of individual landslides established by Rood (1984) to examine relationships between landsliding and failure site characteristics.

Several aspects of this study make the results particularly significant. First, the sample of landslides is very large. This not only allows meaningful statistical generalization, but also permits independent analysis of the relationship between landsliding and failure site characteristics for different landslide types and site characteristics. Consequently, the results of this study should aid the design of further studies of landslides in the Queen Charlotte Islands.

Second, landslides and failure site characteristics are described from medium scale (1:10000) aerial photographs. The results test the possibility that landsliding on the Queen Charlotte Islands can be predicted from the simple and gross variables extracted from NTS maps and medium scale aerial photography. Further testing and ground truthing are required to test the applicability of the results.

Third, the large number of landslides, the wide distribution of the study basins, and the scale of investigation combine to provide a regional approach to studying landslides on the Queen Charlotte Islands.

The overall objective of this study was to examine the effect of site characteristics — slope steepness, aspect, slope shape, slope position, elevation — and regional physiography and geology on landsliding in forested and clearcut terrain. The more specific objectives of the study were:

1. to determine the effect of age on the landslide sediment yield (volume per hectare per year) from clearcut patches;
2. to determine the relationships between site characteristics and the magnitude of different landslide types in forested and clearcut terrain; and
3. to determine the relationships between site characteristics and the yield and frequency (number per square kilometre per year) of different landslide types for forested drainage basins, clearcut patches, and 1-ha clearcut sites.

2 STUDY DESIGN AND METHODOLOGY

2.1 The Study Areas

Annual precipitation in the Queen Charlotte Islands ranges from 1400 mm on the east coast (Port Clements or Masset) to 3000-5000 mm in the Queen Charlotte Ranges. Of more importance to slope failure is the 5-year, 24-hour storm, which delivers in excess of 150 mm of rainfall over most of the Islands (Wilford and Schwab 1982). Other factors that contribute to slope instability include glacially over-steepened slopes, high winds, and frequent seismic activity (Alley and Thomson 1978). Rood (1984) found that natural rates of failure in the Queen Charlotte Islands exceed those observed elsewhere in the Pacific Northwest. The effect of clearcutting on rates of failure is also much more pronounced: average rates of landsliding increase from 20 to 40 times for a 5- to 20-year period following logging.

Landsliding in the Queen Charlotte Islands is confined to steeplands (slopes greater than 20°) on the western one-third of Graham Island, throughout Moresby Island, and on most of the smaller islands lying to the east of Moresby (Gimbarzevsky 1988). This large area includes two physiographic zones — the Queen Charlotte Ranges and Skidegate Plateau (Holland 1976) — and a complex geology consisting of both highly fractured ("soft") and massive ("hard") volcanics, sandstone and conglomerates, limestones, and intrusive granitic rock (Sutherland Brown 1968).

The landslide inventory was collected in 27 study basins distributed between Rennell Sound and Burnaby Island (Figure 1), with a total drainage area of 351 km^2. Seventeen of the basins include some steepland logged area (Table 1). These basins are a subset of a larger sample used for a study of the effect of harvesting activities on fish resources, and include a range of the physical conditions and harvesting situations occurring on the Queen Charlotte Islands.

The steepland logged areas discussed in this report were clearcut between 1 and 17 years before to the dates of aerial photographs. More detail on the age distribution of the clearcut areas is available in Rood (1984). The steepland forested terrain includes only old-growth forest.

The area of forested steepland (Table 1) was defined for each study basin from 1:50 000 NTS maps. Inter-contour distance was used to demarcate areas of slope greater and less than 20°.

Steepland logged areas were extracted from 1:6000 working drawings. Road areas were determined from road lengths measured on working drawings multiplied by a standard width of 20 m.

Study basins lie in both the Queen Charlotte Ranges and Skidegate Plateau physiographic regions. Ten of the basins are located in the Skidegate Plateau (Table 1) and include 40% of the forested steepland area and 65% of the logged steepland area. The other 35% of the sampled logged steepland lies in the Queen Charlotte Ranges (Table 1).

Most of the study area is underlain by the Masset (soft volcanic), Karmutsen (hard volcanic), and Haida and Honna (clastic sedimentary) formations (Sutherland Brown 1968). The sedimentary and highly fractured volcanic formations weather very rapidly compared to the other rocks (Lewis 1982). Only minor occurrences of the other formations are found in the study basins, reflecting their relative abundance over the Skidegate Plateau and Queen Charlotte Ranges.

Surficial material in the basins was not considered in the study.

2.2 Study Design

This study describes the average physiography of the forested part of the study basins, the average physiography of individual clearcut areas, and the areal distribution of the site characteristics associated with individual landslides over the clearcut portion of the study area. The intent is to relate the characteristics of drainage basins, clearcut areas, and individual sites to the landslide data set of Rood (1984).

Although it would have been preferable to describe forested and clearcut terrain by similar techniques so that the landscape characteristics of slope failure could be compared, this was impractical because of the low

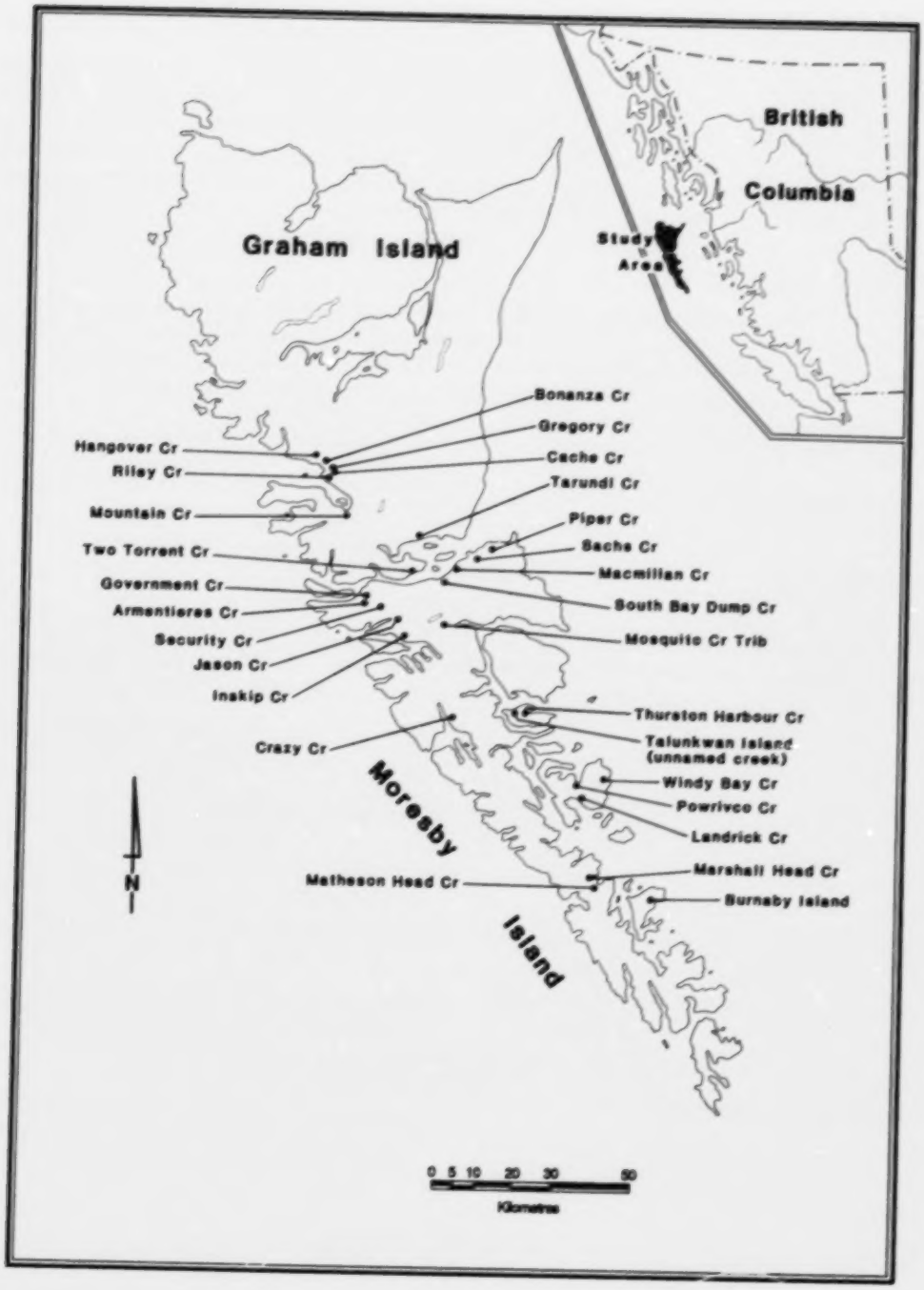


FIGURE 1. Location of study basins on the Queen Charlotte Islands.

quality of 1:50000 maps covering the study basins, the difficulty of describing forested terrain accurately from aerial photographs, and the large forested study area relative to clearcut area (Table 1). Characteristics of the study basins were measured on 1:50000 NTS maps or on larger scale maps provided by the various forest companies. Characteristics of clearcut areas were sampled from 1:10000 aerial photographs or measured from 1:6000 planimetric maps produced from aerial photographs.

TABLE 1. Primary features of the study basins, Queen Charlotte Islands

Basin name	Drainage area (km^2)	Logged[a] area (km^2)	Steepland area[b]		Physiographic[c] region	Geologic[d] formation	
			Forested (km^2)	Logged[a] (km^2)		Major	Minor
Hangover Creek	21.2	0	11.6	0	SP	Masset	-
Bonanza	47.4	6.1	20.4	2.5	SP	Masset	-
Gregory Creek	36.7	0.8	14.5	0.3	SP	Masset	-
Cache Creek	1.5	0.5	0.4	0.03	SP	Masset	-
Riley Creek	28.7	3.5	10.6	1.4	SP	Yakoun	Massett
Mountain Creek	12.8	1.2	9.8	0.4	QCR	PTP	Longarm
Tarundl Creek	11.3	4.0	2.7	0.5	SP	Skidegate	Masset
Piper Creek	4.2	0.4	0.2	0	SP	Haida?	-
Sachs Creek	17.8	11.4	3.6	3.2	SP	Haida	Honna
MacMillan Creek	6.2	4.0	1.8	1.3	SP	Haida	Honna
South Bay Dump Creek	4.0	3.2	0.6	1.4	SP	Honna	Haida
Mosquito Creek Tributary	5.4	1.1	3.8	0.5	QCR	Karmutsen	-
Government Creek	16.1	0	7.7	0	QCR	Karmutsen	PTP,Kunga
Armentieres Creek	4.0	0.8	2.8	0.4	QCR	Karmutsen	-
Security Creek	33.9	1.0	16.7	0.3	QCR	Karmutsen	-
Jason Creek	11.9	0	8.9	0	QCR	Karmutsen	-
Inskip Creek	13.0	0	10.3	0	QCR	Karmutsen	-
Crazy Creek	6.0	0.3	2.8	0	QCR	Haida	Kunga
Talunkwan Island	4.5	1.9	2.0	1.3	QCR	Masset	-
Powrivco Creek	4.3	1.5	1.7	1.2	QCR	Masset	Yakoun
Windy Bay Creek	10.7	0	13.1	0	QCR	Masset	Longarm
Landrick Creek	2.1	1.0	1.1	0.9	QCR	Masset	-
Marshall Head Creek	8.7	0	5.1	0	QCR	Karmutsen	-
Matheson Head Creek	6.7	0	5.0	0	QCR	Karmutsen	-
Burnaby Island	12.0	0	5.8	0	QCR	PTP	Kunga
Two Torrent Creek	3.9	0.3	2.4	0.2	QCR	Haida	Longarm
Thurston Harbour Creek	6.1	3.9	1.3	1.9	QCR	Masset	-
Total	**351.1**	**46.9**	**166.7**	**17.8**			

[a] Includes clearcut and road areas.
[b] Watershed area steeper than 20°. Determined from 1:50000 NTS Maps.
[c] QCR is the Queen Charlotte Ranges; SP, the Skidegate Plateau (Holland 1976).
[d] Geologic formations are from Sutherland Brown (1968). Rock types are (Lewis 1982): Masset - soft volcanics; Yakoun - soft volcanics; Karmutsen - hard volcanics; Haida - clastic sedimentaries; Honna - clastic sedimentaries; Kunga - limestones and argillites; Longarm - clastic sedimentaries; PTP (post tectonic plutons) - granites and granite-like rocks. Major and minor distinctions reflect the geologies that have the majority and minority of mass wasting occurrence in a particular basin.

2.3 The Sample of Landslides

2.3.1 Landslide types

The landslides identified in the study basins were either debris slides or debris flows. Slides and flows were distinguished by their characteristic appearance on the aerial photographs.

Debris slides were typically steep, straight swaths with near parallel sides on hillslopes, and debris was usually deposited in a concentrated area at a change in slope. Debris slides, as used in this study, include the debris slides and debris avalanches of Swanston (1969, 1976) and Varnes (1978). The debris slides were further subdivided into those failures initiating on open slope, gully headwall, gully sidewall, and active wall positions. The gully headwall was defined as the distinct land facet upslope of the incised portion of the gully contributing water and sediment to the gully. Active wall failures included those where debris was not visible and the scar might represent a debris slide, an exposure of bare bedrock, or an extensive zone of steep active gully wall.

Debris flows were identified by signs of flowage (log levees, super-elevation on bends) and the nature of the deposit, which was typically in a gully, elongated, and on a relatively shallow angle. These events include the debris torrents of Swanston (1969, 1976).

Debris flows in forested terrain were subdivided into those failures initiating on open slopes and those initiating in gully headwall or sidewall positions. The initiation points of logged failures were subdivided into open slope, gully, and road locations (see Appendix 1).

2.3.2 The landslide data set

The landslides inventory consists of 729 debris slides and 78 debris flows in forested terrain, and 463 debris slides and 67 debris flows in clearcut terrains (Rood 1984).

The landslides discussed in this report were identified in an inventory of all failures within certain age and size limits for each study basin, from the aerial photographs described in Section 2.3.3. Landslides observed in forested areas ranged in age from less than 1 year to 100 years or more. Older events have progressively greater ground cover, and a point is reached where the required site information can no longer be collected for the feature. This seems to occur for failures from 40 to 60 years in age. Revegetated failures older than this were not sampled.

The minimum size failure that could be adequately identified in both forested and logged terrain was 200 m^2 in area.

The site characteristics measured at the initiation point, as well as the landslide descriptions, are described in Appendix 1.

2.3.3 Aerial photography

The data for this study were collected from two different sets of aerial photographs. Data for the Rennell Sound basins were extracted from 1:11 000 British Columbia government black and white aerial photographs (BC 81059 and BC 81083), flown on July 2 and 24, 1981.

Colour photographs (BCC 325 and BCC 326) of 1:13 000 nominal scale were used for the remaining basins. These photographs were taken between August 27 and September 3, 1982.

Data were extracted from overlapping pairs of these photographs with a WILD A6 stereoplotter. Details about precision and operation are available in Rood (1984).

2.4 Landscape Description

2.4.1 Forested watershed physiography

The 1:50 000 NTS maps were used to measure the drainage area, total steepland area, drainage relief, elevation distribution of steepland area, and average slope. Drainage area and steepland area were planimetered from the maps: steepland areas were those with slopes in excess of 20° as defined by the inter-contour distances. Drainage relief was measured as the differences between the highest and lowest contour elevation within the watershed.

The steepland area was divided into elevation bands of 0-200 m (0-650 ft); 201-350 m (651-1150 ft); 351-500 m (1151-1650 ft); 501-650 m (1651-2150 ft); and greater than 651 m (2151 ft). The average

steepland elevation was calculated as an areally weighted average of the elevation band midpoints.

The average slope of the total basin and the steepland area was defined as (Wentworth 1930 and citations therein to Finsterwalder and Penck):

$$\text{average slope tangent} = \frac{\text{contour interval (m)} \times \text{contour length (m)}}{\text{total area (m}^2\text{)}}$$

Contour lengths were measured with an opisometer (chart wheel).

2.4.2 Clearcut area physiography

The logged portions of the study basins were reviewed and 42 clearcut patches from 12 basins were selected for further analysis according to the following criteria:

1. The area was clearcut during one year.
2. The patch exhibited a reasonably uniform aspect.
3. The area either occurred entirely on slopes over 20° or the proportion of clearcut steepland could be determined.
4. The volume and number of landslides that initiated within the clearcut and along the road area could be measured.

The 42 patches ranged from 9 to 106 ha and had road lengths of between 500 and 6000 m.

For each clearcut patch, a planimetric map of the steepland area and drainage and road networks was drawn at a scale of 1:6000 from the aerial photographs. The maps were used to measure the steepland area, total steepland gully length, total steepland road length, and the distance from the bottom of the steepland area along the drainage net to a stream.

2.4.3 Site characteristics of clearcut areas

To determine the areal distribution of site characteristics the steepland clearcut areas were sampled on a rectangular grid having 100-m centres. At each sample point the following characteristics of the landscape were measured from the aerial photographs (see Appendix 1):

1. Type: whether the point is part of an open slope, gully headwall, or gully sidewall. This describes plan slope shape: open slopes are often convex or straight in plan; gullies are concave.
2. Average slope: determined from the elevation difference measured over a distance of 30-80 m centred on the sample point.
3. Aspect: the compass direction, to the nearest 5°, that the slope segment faces.
4. Elevation: the elevation, to the nearest 5 m, of the sample point above sea level.
5. Slope shape: the profile of the hillslope from approximately 50 m above to approximately 50 m below the sample point. Described as concave (steeper slopes above than below), convex (steeper slope below than above), straight, or complex. Complex slopes include benched slopes as well as complex combinations of slope elements.
6. Slope position: the position of the sample point between a local base level and a height of land. Described as bottom, mid, or top.

As well, physiographic region was interpreted from Holland (1976) and bedrock formation was interpreted from 1:125 000 maps in Sutherland Brown (1968). These same characteristics were measured at each landslide initiation point.

2.5 Factors Confounding Analysis

For the observational experimental design used, three factors confound analysis of the data: age variation in clearcut areas, slope, and landslide types. First, in logged terrain the frequency and yield from a particular area strongly depend on both the length of time since clearcutting (representing root deterioration) and the timing of major storms following logging.

Second, slope strongly influences shallow landslides and could confound relationships between landsliding and site characteristics. That is, failure may occur only on particularly susceptible sites at lower gradients, but under a broader range of conditions on steeper slopes.

Third, results could be confounded by the combination of different types of landslides and initiation positions in the landscape. Debris sliding and debris flowage are different processes initiated under different conditions; as well, each process has a different characteristic magnitude and frequency. Clearcutting influences the magnitude and frequency of both debris sliding and debris flows in different ways (Rood 1984). Comparable data sets require four categories: clearcut and forested debris slides, and clearcut and forested debris flows. Debris slides should also be subdivided into open slope and gully categories. At the very least, combining open and gully slides may bias results if gullying is strongly associated with particular combinations of physiographic and geologic formations. At worst, debris sliding on open slopes and in gullies may be associated with an entirely different suite of variables.

3 LANDSLIDING IN FORESTED WATERSHEDS

For forested watershed or drainage basins of several square kilometres or larger, many of the local factors causing landsliding are integrated or averaged out and landsliding rates may be related to a relatively simple set of variables describing the basins. In the study basins on the Queen Charlotte Islands, the measured physiographic variables are independent of basin area, so it is possible to compare landsliding for different physiographies and geologies without concern for drainage area (Table 2; Figure 2).

Study basin physiography differs slightly in the Queen Charlotte Ranges and the Skidegate Plateau. The principal differences are less steep slopes and smaller steepland areas on the Plateau (see Table 3). While the less steep slopes produce a lower average rate of open slope landsliding, the total yields are similar because debris flow yields are not well correlated with slope steepness (see Table 4).

TABLE 2. Significance levels for correlations between drainage area and other basin attributes

Variable	Degrees of freedom	F-statistic	Level of significance*
Basin average slope	25	2.30	0.15
Steepland average slope	25	0.14	70.2
Drainage relief	25	3.18	0.09
Average steepland elevation	25	.47	0.2
Percentage of steepland area	25	1.83	0.19

* Indicates relationships significant at $p = 0.05$.

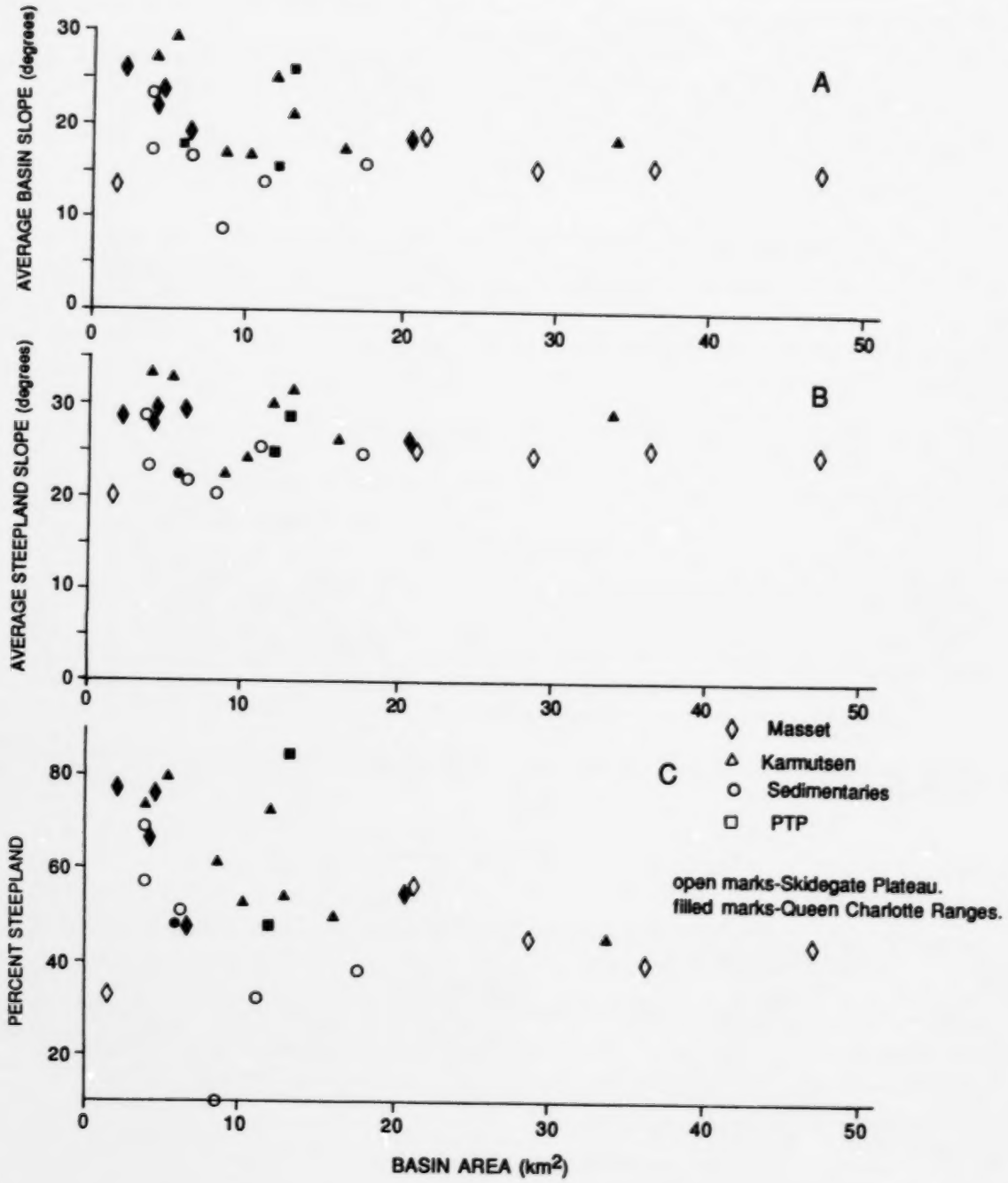


FIGURE 2. The relationship of average basin slope, average steepland slope, and percent steeplands to forested basin area.

TABLE 3. Weighted average physiography and sediment yield of basins in the Skidegate Plateau and Queen Charlotte Ranges

Variable	Areally weighted average	
	Skidegate Plateau	Queen Charlotte Ranges
Total drainage area (km²)	182.7	171.6
Steepland elevation (m)	370	350
Drainage relief (m)	630	690
Steepland slope (degrees)	25.1	27.7
Percentage of steeplands (%)	43.5	57.3
Yield from open slope debris slides (m³/ha per year)	0.65	0.81
Yield from gully debris slides (m³/ha per year)	0.42	0.41
Yield from debris flow (m³/ha per year)	0.65	0.56
Total yield (m³/ha per year)	1.72	1.78

TABLE 4. Relation of landsliding yield to average steepland slope

Variable	R^2	b_y[a]	b_f[a]	SE (m³/ha per year)	Range[b] (m³/ha per year)	Significance
Open slope debris sliding yield	0.40	0.111	0.122	0.54	0-2.65	0.005
Gully debris sliding yield	0.38	0.083	0.086	0.37	0-2.33	0.001
Debris flow yield	0.14	0.050	0.054	0.51	0-1.67	0.117

[a] b_y and b_f are the slopes of the regression and the functional relationships. $\lambda = 0.25$ was calculated from error variances in Mark and Church (1977; Table 1).

[b] N = 23, excluding South Bay Dump Creek, Talunkwan Creek, Thurston Harbour Creek, and Powrivco Creek because these basins are mostly logged.

TABLE 5. Functional slopes for the relation between landsliding yield and average steepland slope for different bedrock formations

Bedrock formation[a]	N	R^2	b_f	SE (m³/ha per year)	Range (m³/ha per year)	Significance
Masset	7	0.23	.386	1.0	0.00-2.9	0.20
Karmutsen	8	0.34	.350	1.4	0.63-5.34	0.14
All sedimentaries	6	0.59	.402	0.8	0.00-2.12	0.20

[a] Sutherland Brown, 1968.

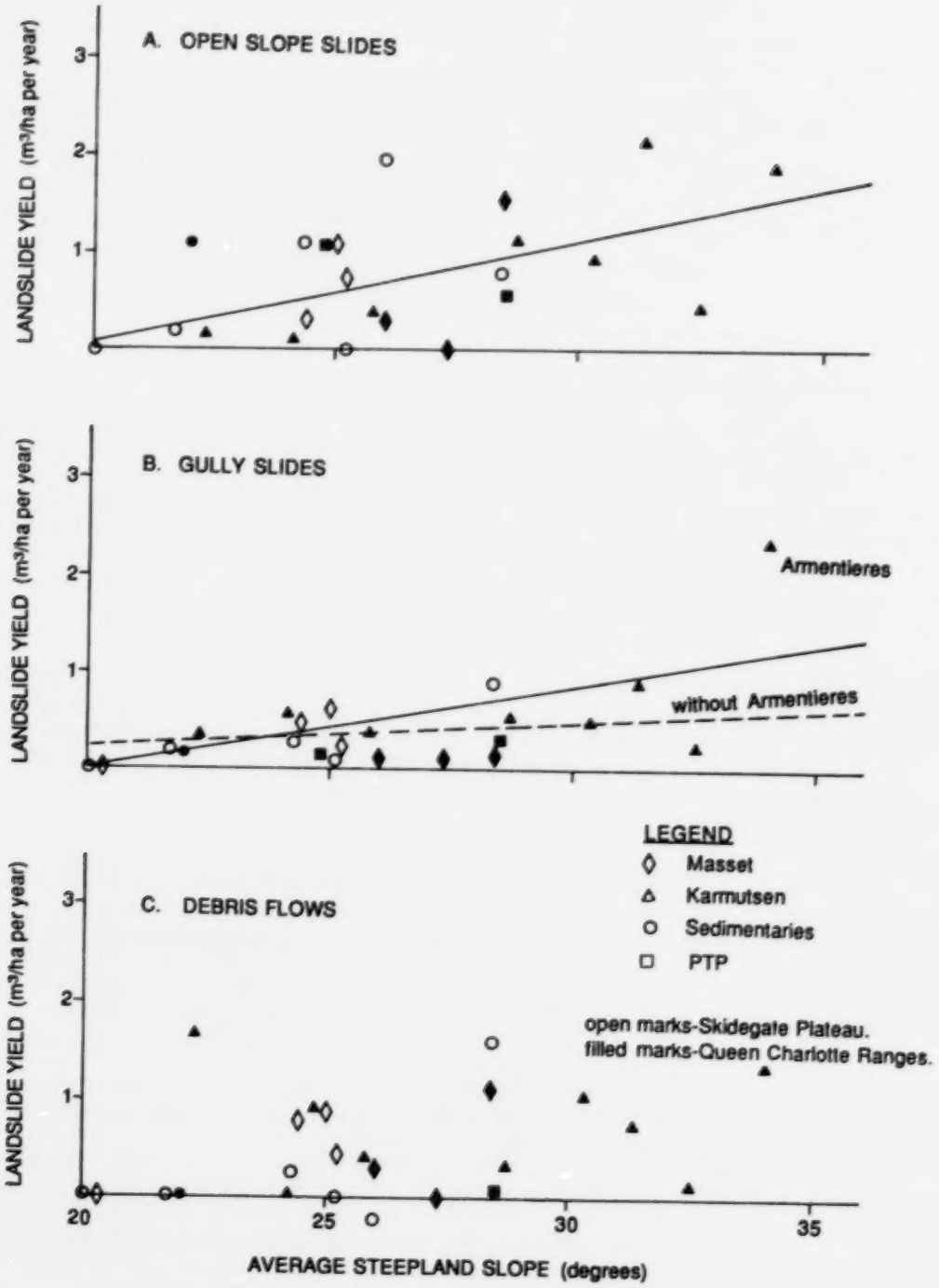


FIGURE 3. The variation of landsliding yield with average steepland slope of the forested basins.

Differences in failure rates at similar steepland slopes are unaffected by bedrock formation (see Figure 3). Similar functional slopes are observed for correlations of failure rates and steepland slopes for each of the different geological formations (Table 5), and it seems reasonable to conclude that regional geology has no influence on yield at the level of individual watershed.

The correlation coefficients reported in Chapter 3 and 5 are often low even though they define significant relationships. This often occurs for natural processes, where many variates are collinear.

3.1 Open Slope Debris Sliding

Open slope landslide yield is correlated with average steepland slope, although the relationship is weak (Figure 3A; Table 4) because of the strong, non-linear increase of landsliding rates with slope at the site (see Section 7.2). Open slope failure rates are controlled by the distribution of steeper slopes (35°) which may or may not be reflected in the average slope calculated from 1:50 000 NTS maps. Essentially, only a small portion of the area of most basins is involved in active landsliding.

3.2 Gully Debris Sliding

Gully debris sliding yields are also correlated with steepland slope (Figure 3B; Table 4). The relationships shown in Table 4 are profoundly influenced by the large rate observed in Armentieres Creek. Removal of this basin lowers the slope of the regression to 0.038 and R^2 to 0.26 ($p = 0.014$). Open slope slides exhibit a much more rapid increase of yield (approximately 3x) with increasing slope than do gully failures, particularly when Armentieres Creek is removed from the data set. This likely occurs because the slopes calculated from 1:50 000 NTS maps reflect open slopes rather than slopes in the gullies, and because gully densities vary between the study basins. Slopes in gullies may differ from open areas depending on the overall profile of slope, the degree of gully incision, and the nature of the gully walls.

3.3 Debris Flows

Debris flows are commonly triggered by debris slides entering or originating in gullies. In this study, 14% of the flows from forested areas were triggered by open slope slides, 15% by sidewall slides, and 57% by headwall slides. Fourteen percent were of unknown origin. Consequently, debris flow yields are correlated with gully failure frequency ($R^2 = 0.48$; $SE = 0.39$; $p = 0.02$). On average, one debris flow in forested areas occurs for each 3.3 gully debris slides.

Debris flow yields are not significantly correlated with any of the other physiographic or yield variables, nor do these other variables provide any significant improvement in a multiple variable model with gully failure rates. It seems likely that unmeasured variables, such as the density of gullies in steepland areas, may provide more practical correlates with debris flow yield. However, these cannot be satisfactorily extracted from 1:50 000 maps.

3.4 Landslides Entering Streams

The volume of material entering streams depends on, at least, the size of landslides occurring (Rood 1984), the type and number of landslides, and the characteristics of the drainage basin, such as the presence or absence of foot slopes. In the forested basins, approximately 40% of the yield to streams is from open slope debris slides and approximately 50% is from debris flows.

A multiple regression model to explain yield to streams should include average steepland slope, gully debris slide frequency, and the proportion of steeplands in the basin. All these variables, as well as the frequency of open slope failures, are significantly correlated with the yield to streams (Table 6). Because of the inter-correlation of the independent variables, relatively little improvement in explanatory power is achieved by using a multiple variable approach compared to, simply, the gully slide frequency.

TABLE 6. Correlations of physiography and landslide frequency with the yield to streams

Variable	R^2	SE	Level of significance
Average steepland slope	0.30	0.76	0.01
Gully slide frequency	0.58	0.60	0.01
Proportion of steeplands	0.21	0.81	0.05
Open slope slide frequency	0.32	0.76	0.01

Several different multiple regression equations can be developed to predict yield to streams (YS). Based on physiographic variables that can be measured on 1:50000 maps:

$$YS = -2.46 + .11AS + 0.006PS \quad (R^2=0.31; SE=0.78) \qquad (2)$$

where, AS is average steepland slope (in degrees) and PS is the proportion of steeplands (%). Where large scale aerial photographs are available the best equations are:

$$\text{No footslope: } YS = 9.0SF - 0.07 \ (N=12; R^2=0.58; SE=0.69) \qquad (3)$$

$$\text{footslope: } YS = 1.9SF + 0.2 \ (N=11; R^2=0.09; SE=0.36) \qquad (4)$$

where, SF is the total slide frequency (the sum of gully and open slope slides). Basins with and without significant footslopes were distinguished on 1:50000 maps. In larger basins, portions of the drainage may have footslopes; other portions may not. This complicates classification. Equation (4) for stream yield from basins with footslopes is not significant. Further discussion of the factors affecting the yield to streams is in Section 5.7.

4 THE SITE CHARACTERISTICS OF LANDSLIDES IN FORESTED TERRAIN

4.1 The Relation of Landslides to Site Characteristics

The total landslide volume associated with a given site characteristic can be treated as the product of three factors:

1. the size distribution of the landslides associated with the characteristic (for example, north aspects);
2. the frequency of landsliding per square kilometre for the particular site characteristic; and
3. the total area of landscape covered by the particular site characteristic.

The first item — landslide size or magnitude — can be directly examined. Without sampling the landscape it is not easy to unravel the relative importance of variations in area and variations of failure frequency to the number of landslides observed for different site characteristics.

The effect of the various confounding factors is difficult to assess. It seems reasonable to assume that the relationship between site conditions and the magnitude of landslides would be unaffected by age in forested or clearcut areas, but that it may be influenced by slope angle. Consequently, the data set was split into those landslides with slopes greater and less than 37°. Similar conclusions were drawn for each of the two slope groups, so results are only reported for the total data set.

4.1.1 The volume distribution of landslides

The distribution of slide numbers is non-normal and may follow a Poisson distribution (Figure 4). Several observations can be made about the distribution of clearcut and roaded slides relative to forested slides:

1. The cumulative volume distribution from roads is similar to that from forested terrain (Figure 4).

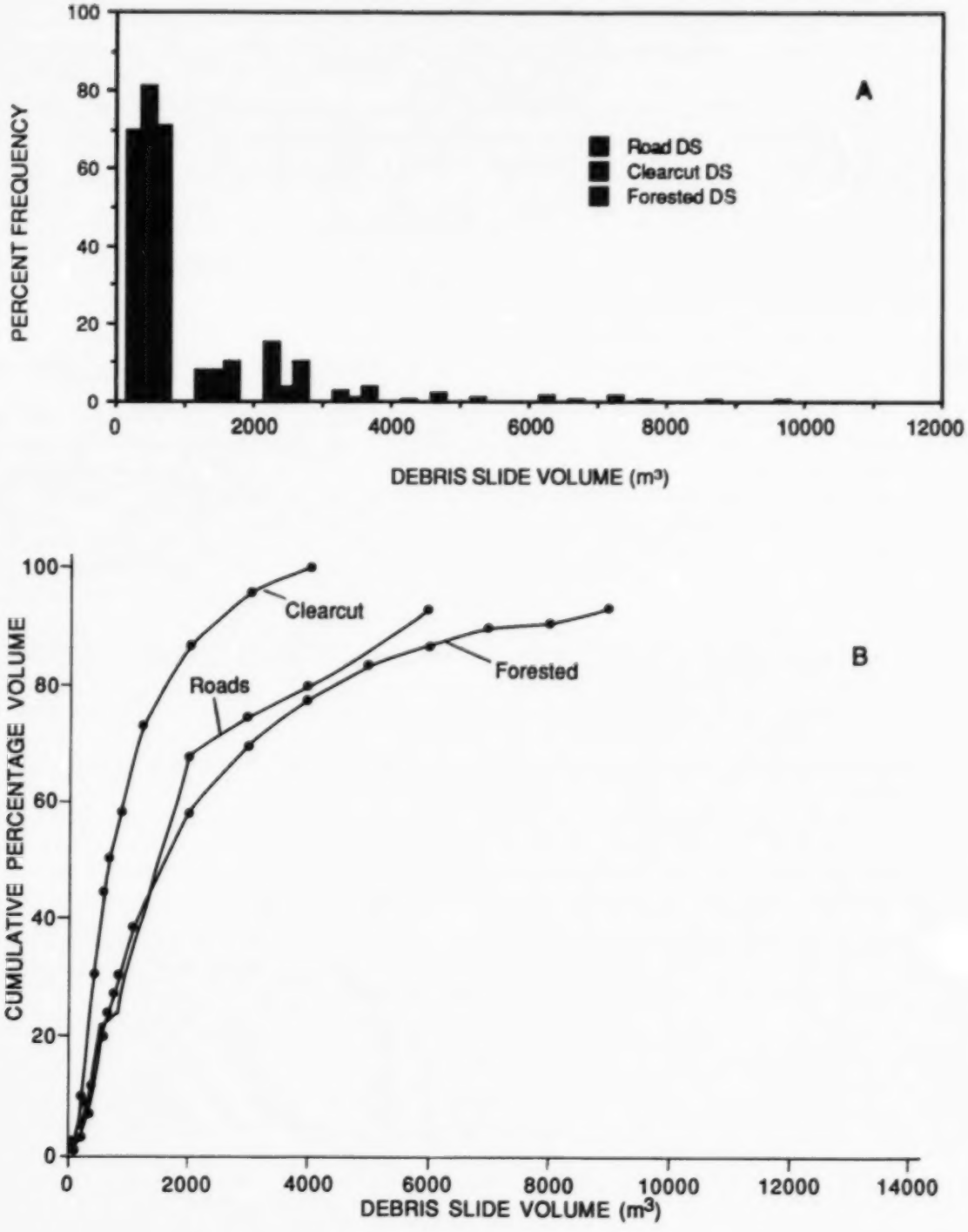


FIGURE 4. The frequency and cumulative volume distribution of forested, clearcut, and road debris slides, Queen Charlotte Islands.

2. The cumulative volume distribution of clearcut debris slides is of similar form but of smaller average size than in forested terrain. The overall range of events is smaller and a larger proportion of the total volume is the smallest slide category.

3. Average volumes calculated for different landslide categories are very sensitive to the numbers of large failures. Debris slides exceeding 4500 m^3 occur at a rate of approximately one per square kilometre in forested areas. While some of these larger slides are older events, it seems unlikely that the dearth of larger slides in clearcut areas is due to sample area differences. Reneau and Deitrich (1987) provide an explanation for the commonly observed smaller sizes in clearcut areas (O'Loughlin 1972; Morrison 1975; Schwab 1983). Root strength along the margin of potential failures determines the minimum failure mass in forested areas, but similar constraints do not apply in clearcuts (Rood 1984).

The distributions of debris flows in clearcut and forested terrain with volumes less than 20 000 m^3 are not dissimilar (Figure 5). Within this range, the median and average sizes are nearly equal for forested and clearcut terrain. The major difference between the average size of debris flows in forested and clearcut terrain, based on the total sample of observed flows, lies primarily in the increased number of very large flows originating in clearcut.

4.1.2 Initiation site characteristics and debris slide magnitude

To test the influence of site characteristics on landslide magnitude, the variation of the median and distribution of debris slide volume over the different categories of slope, aspect, slope shape, slope position, and elevation were examined. The effect of regional geology on bedrock formation was studied. Two tests were applied to the data; the Kruskal-Wallis test of the distribution, and a median test. No analysis of debris flows was undertaken because of the small sample size. Table 7 shows whether the null hypothesis for each variable and landslide type was accepted or rejected. From this it is clear that landslide volume is independent of geology, aspect, and elevation — as well as of slope. In gullies, landslide volumes are independent of site characteristics. For slope shape, the largest debris slides — for forested and clearcut open slopes — occur on concave and complex slopes. Landslides on straight slopes have the smallest median size. For all slope shapes, the largest landslides occur in upper slope positions and the smallest in the lower slopes.

Though not shown on Table 7, the magnitude of landslides from road areas is independent of site conditions, suggesting they are primarily an engineering rather than an environmental problem.

TABLE 7. Kruskal-Wallis statistics for the relation between site characteristics and debris slide volumes

Site characteristics	No. of categories	Open slope slide			Gully headwall slides			Gully sidewall slides		
		N	Statistic	Significance*	N	Statistic	Significance	N	Statistic	Significance
Forested terrain										
slope	7	295	5.26	0.51	186	12.78	0.05	148	4.74	0.58
geology	8	295	15.40	0.03	186	7.44	0.38	148	9.36	0.13
aspect	8	295	9.24	0.24	186	3.49	0.84	148	11.51	0.12
slope shape	4	295	20.55	0.00*	186	2.82	0.42	148	3.53	0.32
slope position	3	295	18.87	0.00*	186	9.05	0.01	148	0.50	0.78
elevation	5	295	9.27	0.03	186	11.75	0.02	148	1.33	0.72
Clearcut terrain										
slope	7	165	10.67	0.10	92	5.50	0.48	61	5.27	0.51
geology	8	165	5.83	0.34	92	7.37	0.19	61	2.21	0.82
aspect	8	165	5.11	0.65	92	3.70	0.81	61	5.30	0.62
slope shape	4	165	18.28	0.00*	92	5.21	0.16	61	3.92	0.14
slope position	3	165	12.60	0.00*	92	2.58	0.28	61	1.96	0.37
elevation	5	165	2.96	0.40	92	1.52	0.68	61	2.92	0.40

* Asterisks mean significant relationship at $p = 0.01$.

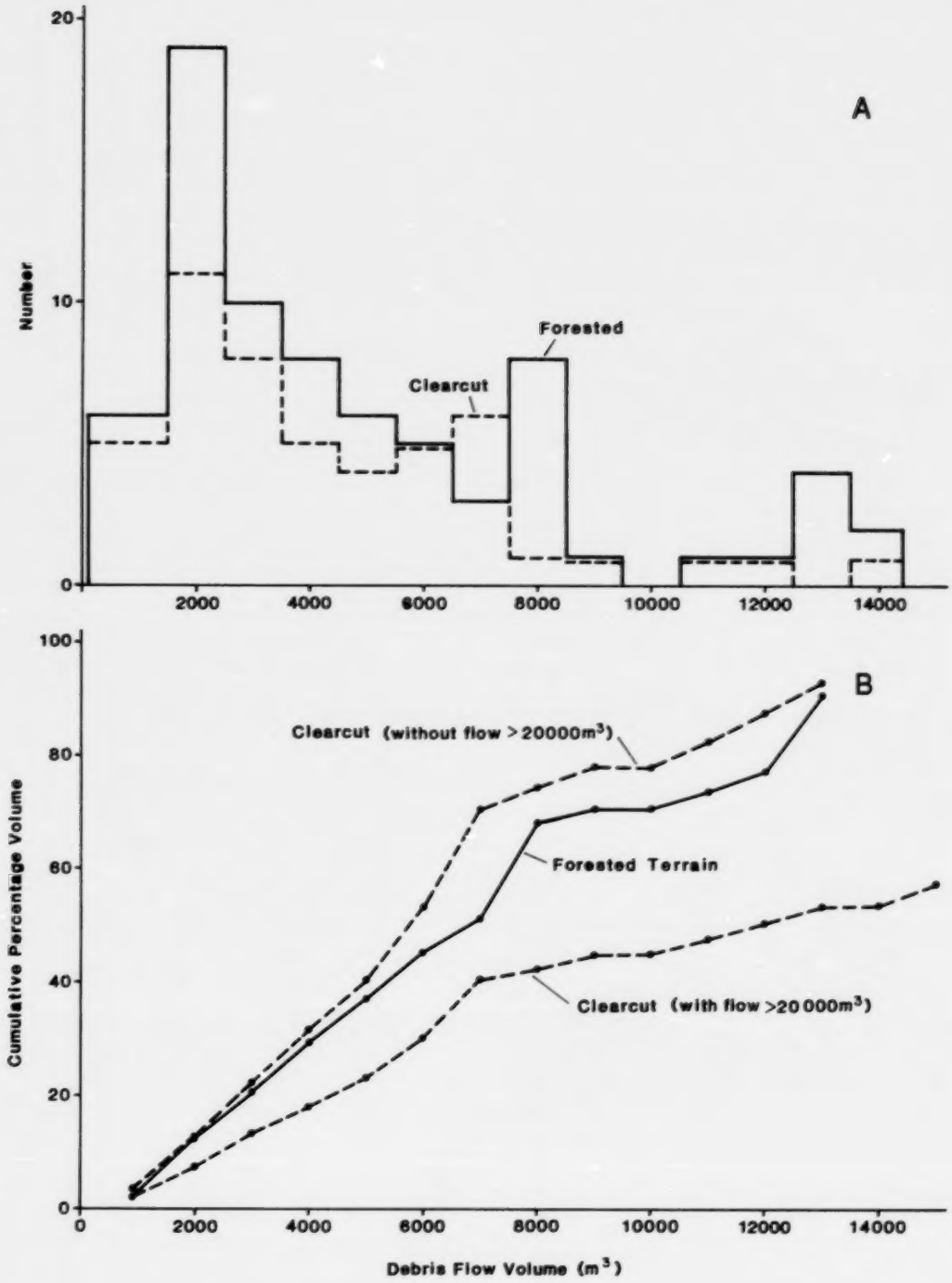


FIGURE 5. The frequency and cumulative volume distribution of debris flows in forested and clearcut terrain, Queen Charlotte Islands.

4.1.3 Initiation site characteristics and the number of landslides

For forested terrain, which was examined from 1:50 000 maps, the landscape area covered by a particular site characteristic was often unknown. Measurements are available only for bedrock formation and elevation. For other site characteristics, the relative importance of varying frequencies and areas to the total number of failures associated with a particular site characteristic must be based on other studies, experience with the terrain on the Queen Charlotte Islands, or a general understanding of landslide behavior.

Statistical testing of the relation between site characteristics and the frequency of landsliding from steeplands was carried out for the data reported in Gimbarzevsky (1988). Only two variables did not significantly influence the frequency of mass wasting: bedrock formation and major physiographic region (Queen Charlotte Ranges, Skidegate Plateau, and Queen Charlotte Lowland). Although significant differences in average frequency were found over the different categories of most of the variables, these were generally not large. For those variables that are adequately described as an average or dominant condition over a 1-km^2 block — aspect, slope position and perhaps elevation — the maximum observed frequency was less than twice the minimum frequency.

In this study, the same technique was used to analyze the variation of numbers of forested landslides with different site characteristics. To generate predicted values for the chi-square test, equal numbers of failures were assigned to each category or, if areas were measured, equal frequencies were assigned. Table 8 illustrates the acceptance or rejection of the null hypothesis for each site characteristic. The distribution of debris slides is non-random for nearly all site characteristics.

Table 8. Acceptance or rejection of the null hypothesis for a relation between environmental variables and debris slide numbers

Variable	No. Categories	No. Slides	X^2	Significance[a]	Expected values
Open Slope Slides					
Slope	7	295	153.9	.001*	equal proportions
Aspect	8	295	63.1	.001*	equal proportions
Slope shape	4	295	111.5	.001*	equal proportions
Slope position	3	295	60.2	.001*	equal proportions
Elevation	5	295	39.8	.001*	portion of total area[b]
Bedrock formation[c]	9	295	12.8	0.12	portion of total area[b]
Gully Headwall Slides					
Slope	7	186	91.8	.001*	equal proportions
Aspect	8	186	26.2	.001*	equal proportions
Slope shape	4	186	179.1	.001*	equal proportions
Slope position	3	186	110.0	.001*	equal proportions
Elevation	5	186	22.6	.001*	portion of total area[b]
Bedrock formation[c]	8	146	24.2	.001*	portion of total area[b]
Gully Sidewall Slides					
Slope	7	146	75.3	.001*	equal proportions
Elevation	5	146	59.0	.001*	portion of total area[b]
Bedrock formation[c]	8	146	24.2	.001*	portion of total area[b]

[a] Asterisks indicate relationships significant at p = 0.99.
[b] Expected values are calculated from the portion of the total area (including open and gullied slopes) in each category. This adequately reflects the variation of open slope areas, but may not suitably describe gully areas.
[c] Sutherland Brown, 1968.

4.1.4 Slope and landsliding

In forested terrain, 57% of the total volume of open slope debris slides was found to initiate on slopes between 36 and 45°, and 92% of the total volume is from slopes between 31 and 50° (Figure 6). A similar pattern occurs in clearcut terrain, with approximately 49% of open slope debris slide volume initiating from slopes between 36 and 45° and 87% of the volume from slopes between 31 and 50°. A major step in the distribution is apparent at 30° for the open slope distributions.

A similar pattern emerges for the distribution of the number of failures over the slope classes. The bulk of the failures in both clearcut and forested terrain are concentrated between 31 and 50°. The class interval with the largest number of failures in both cases is from 36 to 40°. These histograms correspond closely to those reported by Rollerson (1984; his Figure 3.4.1) for the Queen Charlotte Islands and Southwestern Vancouver Island.

There are some minor differences in the slope of initiation points in clearcut and forested open slope positions. Relative to the forested terrain, clearcut open slope debris slides occur on lower slope angles. The average open slope initiation angle in clearcut is 37.2°; in forested terrain it is 40.3°. These are significantly different at the 99% confidence level (t-test; similar variance assumption is met). Differences may result from increased failure at lower gradients (which are due to root mat deterioration) or from a lack of logging on the steepest slopes.

In both forested and clearcut gully terrain, approximately 75% of the total volume initiates on slopes ranging between 36 and 50° (Figure 7). Compared to open slope slides, a larger proportion of the gully volume comes from steeper slopes.

Most of the slides occur on slopes between 36 and 50°, though a greater number of the clearcut slides occur on more shallow slopes (Figure 7B). The average initiation slope in clearcut gully terrain is 38.8°, while that in forested terrain is 41.6°. As with open slope slides, these differences may reflect increased failure on lower gradient slopes (due to root mat deterioration) or a lack of logging on steeper slopes. Of more interest, the average initiation slopes in gullies in both forested and clearcut terrain are significantly greater than the respective average initiation slopes on open slopes.

4.1.5 Aspect and landsliding

The lowest numbers of both open slope and gully failures occur on west-, northwest-, and north-facing slopes (Figure 8A). The greatest proportion of forested open slope failures are on southwest-, south-, and northeast-facing slopes. Gimbarzevsky (1988) also observed maximum frequencies from south through northeast aspects.

These relationships are the opposite of those typically expected under the weather and climate regime of the Queen Charlotte Islands. West- and north-facing slopes would normally be exposed to frontal disturbances; east-facing slopes would be expected to experience some rain shadow. For these conditions, greater numbers of slides would be expected on west through north aspects.

4.1.6 Slope shape, slope position and landsliding

The bulk of failures (more than 70% of the total) occur on concave and straight slopes. This reflects, in part, the distribution of slope types over the study area. Open slope debris slides occur predominantly on concave slopes, while gully debris slides occur in greatest numbers on concave and straight slopes (Figure 8B). This bimodal pattern occurs because headwall slides often occur on steep upper-slope concave slope segments, while sidewall debris slides occur on straight lower slope wall segments.

Forested open slope debris slides occur predominantly on mid- and upper-slope positions: few occur in lower positions (Figure 8c). Nearly equal proportions of gully failures occur on upper and lower slopes, but very few in mid-slope positions. These proportions correspond to headwall slides on upper slopes and sidewall slides on lower slopes. A similar variation for landsliding frequency was observed by Gimbarzevsky (1988). Slope position is confounded with slope shape, and the relationship seems to

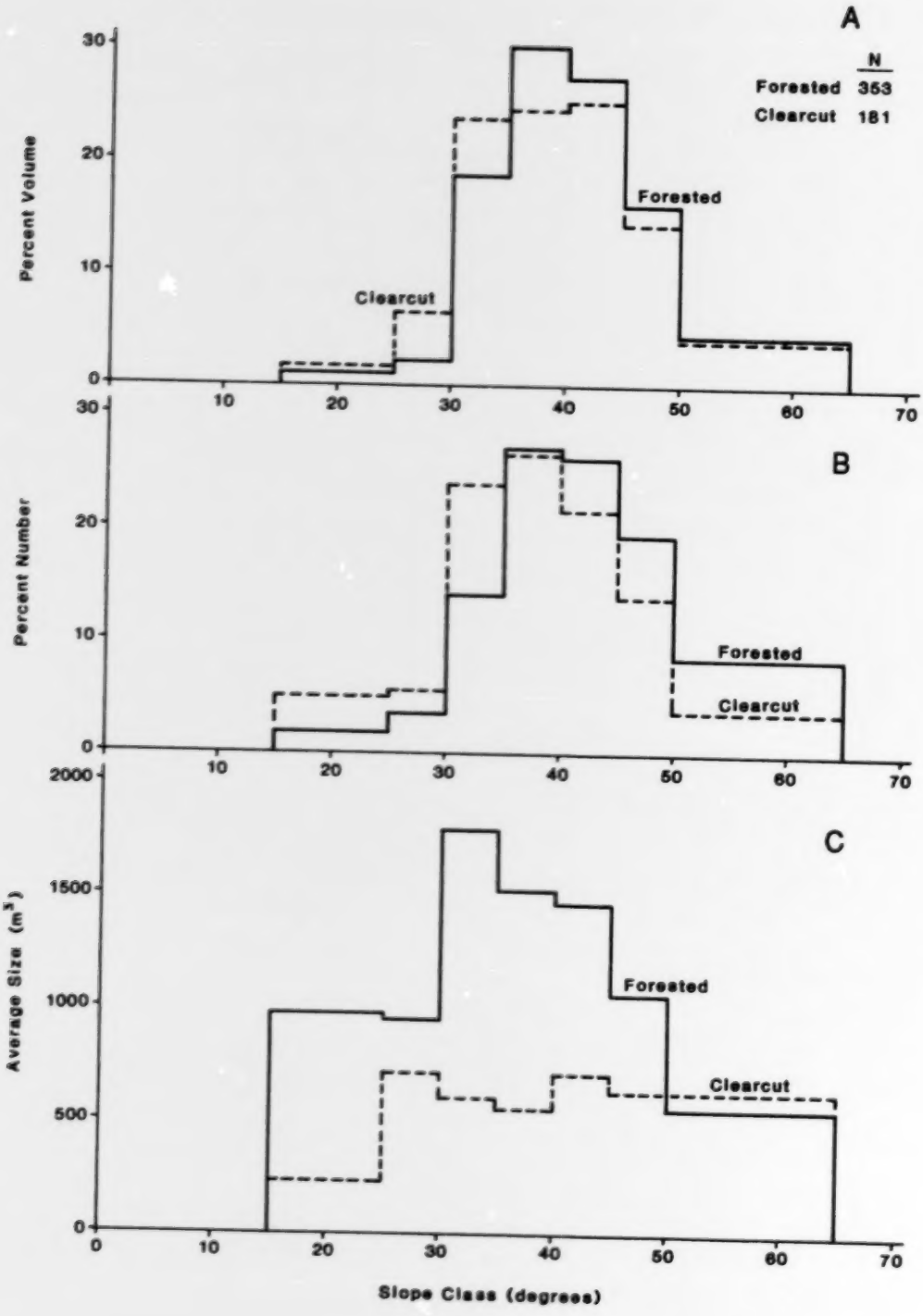


FIGURE 6. The volume, number and average size of open slope debris slides in forested and clearcut terrain over seven slope classes.

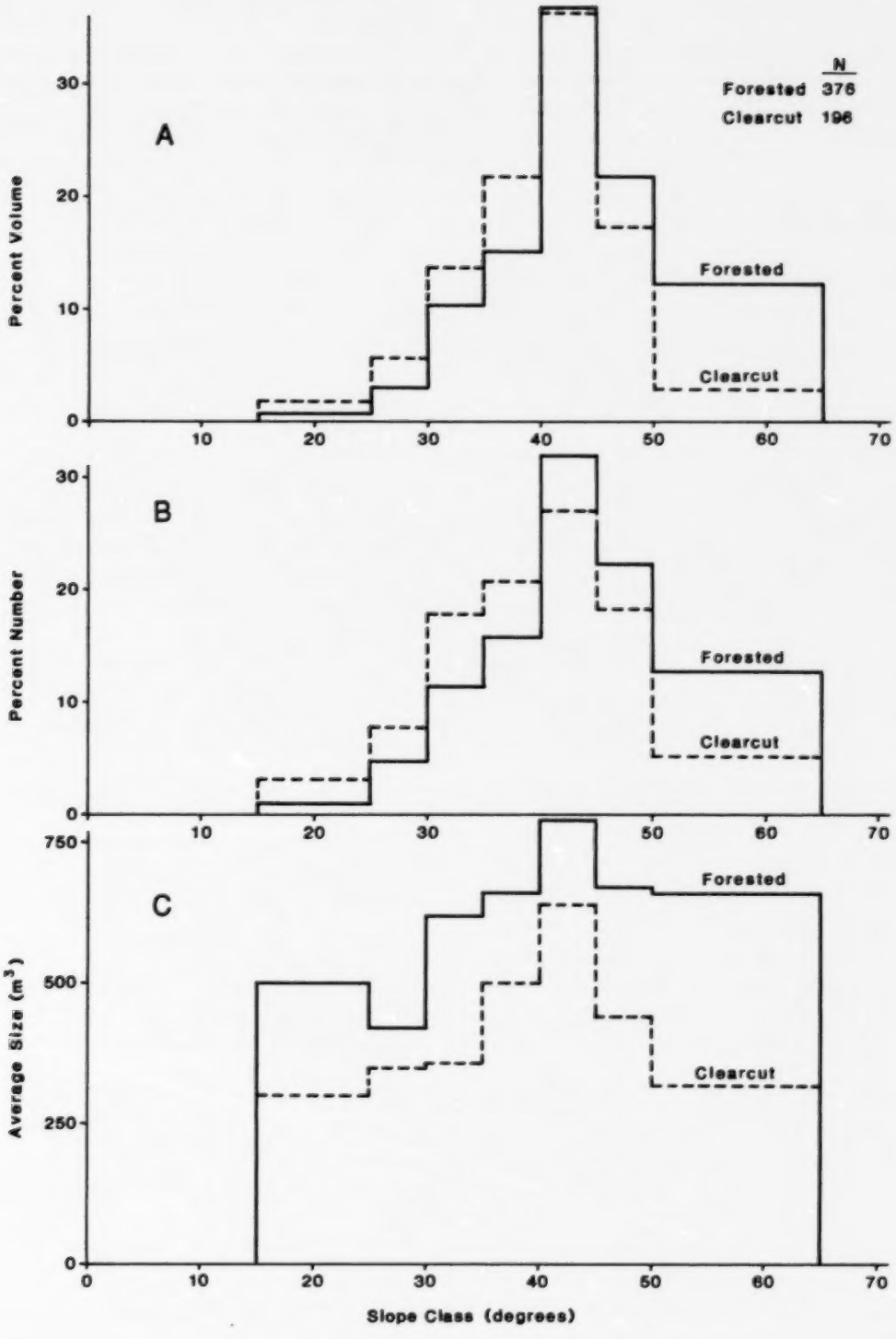


FIGURE 7. The volume, number and average size of gully debris slides in forested and clearcut terrain over seven slope classes.

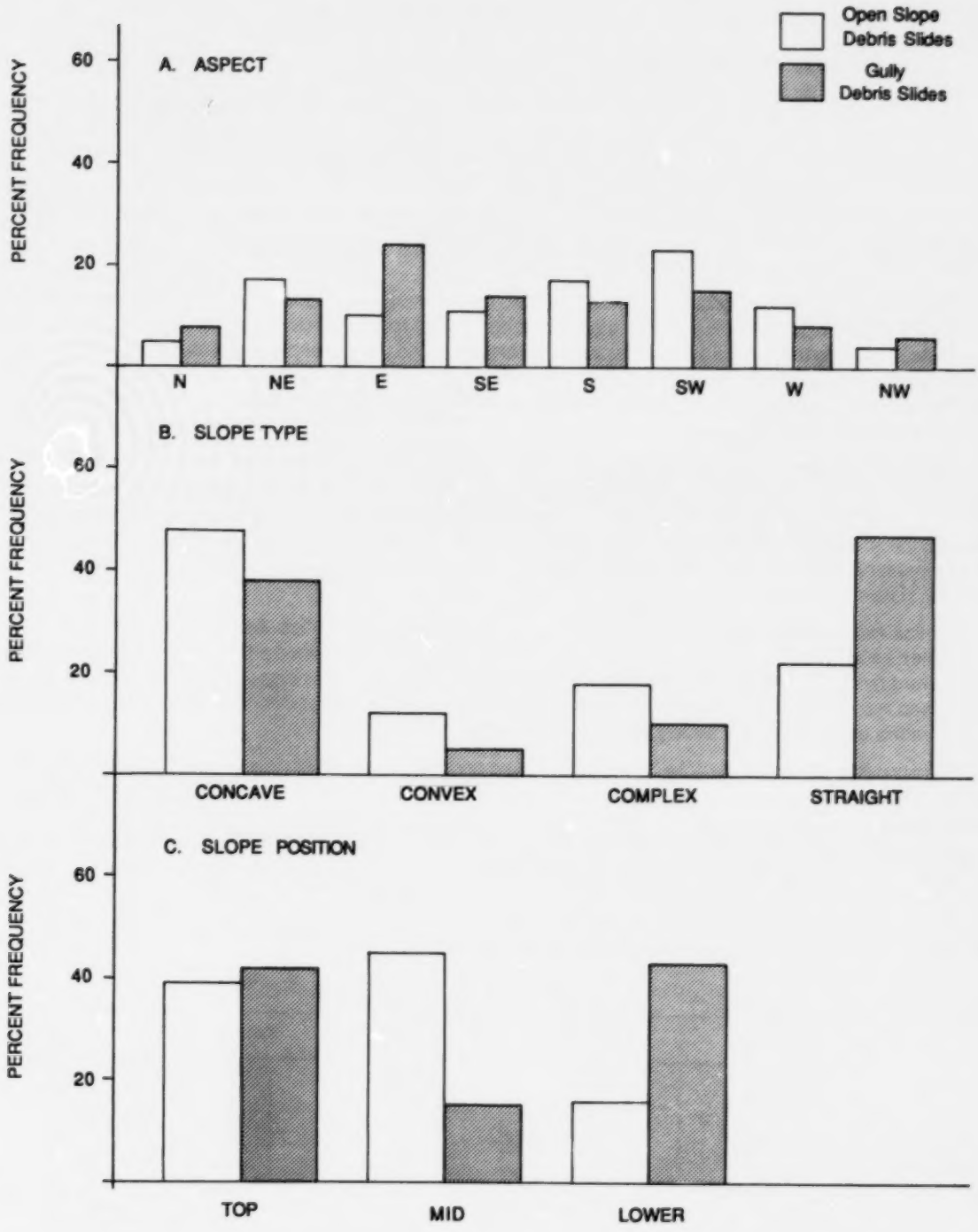


FIGURE 8. The distribution of open slope and gully debris slides over different aspects, slope types, and slope positions in forested terrain.

reflect the pattern of slope shapes and the distribution of steep slopes on the Islands. Slopes are often concave — the steepest portions occur in the upper-slope positions — and, as a result, a large proportion of steep slopes occur at higher elevations or on upper slopes.

4.1.7 Geology and landsliding

Figure 9 shows the landsliding frequency over elevation and geologic formation. Frequencies were calculated from the steepland area of each geologic formation (Sutherland Brown 1968) or elevation band within the study basins, and an age of up to 40 years was assumed for forested debris slides. The figure shows the greater importance of gully debris slides on sedimentary formations.

5 LANDSLIDING IN CLEARCUT AREAS

The clearcuts typically occupy an area between the spacing of the grid sample (each point represents 1 ha) and a drainage basin. Landslide yields can be related to the gross characteristics of the individual clearcuts, including the elapsed period between clearcutting and the aerial photography, and average angles of the open slope, gully headwall, and sidewall portions of the clearcut. Variables that control landsliding may be different than those for forested basins (Chapter 3) or forested or clearcut sites (Chapters 4 and 6) because of their integration over different landscape areas.

Clearcut characteristics were measured from 1:6000 maps produced from aerial photographs or calculated from the 100-m grid sample of sites lying within the clearcut patch. Different variables are available than can be extracted from 1:50 000 maps. The density of gullies and roads was measured; the proportion of open slope, headwall, and sidewall areas was known and average slopes and slope distributions could be calculated for each landscape type. Landsliding rates are calculated for the areas of open slope, gully headwall or gully sidewall terrain.

Yields rather than frequencies were related to clearcut characteristics, because the yields are better correlated with patch characteristics than frequencies. Using yields produced a minor confounding effect due to different landslide magnitudes on different site characteristics on open slopes (Section 4.1.2). The yields discussed in this section are often expressed as volumes per hectare rather than volumes per hectare per year because the time since clearcutting has little effect on landslide yields.

The clearcut areas primarily lie on the Masset and sedimentary geologic formations (Table 9). Variation of landsliding rates among the different geologies is due to different slopes and is confounded by different timing of clearcutting relative to the date of aerial photography and the passage of major storms. Even under these circumstances, there is relatively little difference in landsliding. The lower rates observed in open slope sedimentary positions are due to lower average slopes, as well as to a lack of slopes exceeding 35° (see Section 6.2).

TABLE 9. Description of the physiography and landsliding yields for different geological formations in the clearcut areas

	Masset	Yakoun	Karmutsen	Sedimentaries[a]
Area (ha)	864	164	64	629
Average open slope (°)	28	28	29	26
% open slope over 35°	12	15	16	5
Average headwall slope (°)	31	30	36	29
Open slope yield (m^3/ha)[b]	95	86	105	30
Gully yield (m^3/ha)[b]	125	90	75	99
Debris flow yield (m^3/ha)[b]	108	84	101	147
Est. average age (yr)	5.3	5.4	9.7	8.1

[a] Includes Haida and Honna formations.

[b] Calculated as observed volume divided by open slope, gully headwall, and total area. Values are not converted to a per-year basis because of the complex distribution of ages on the different formations.

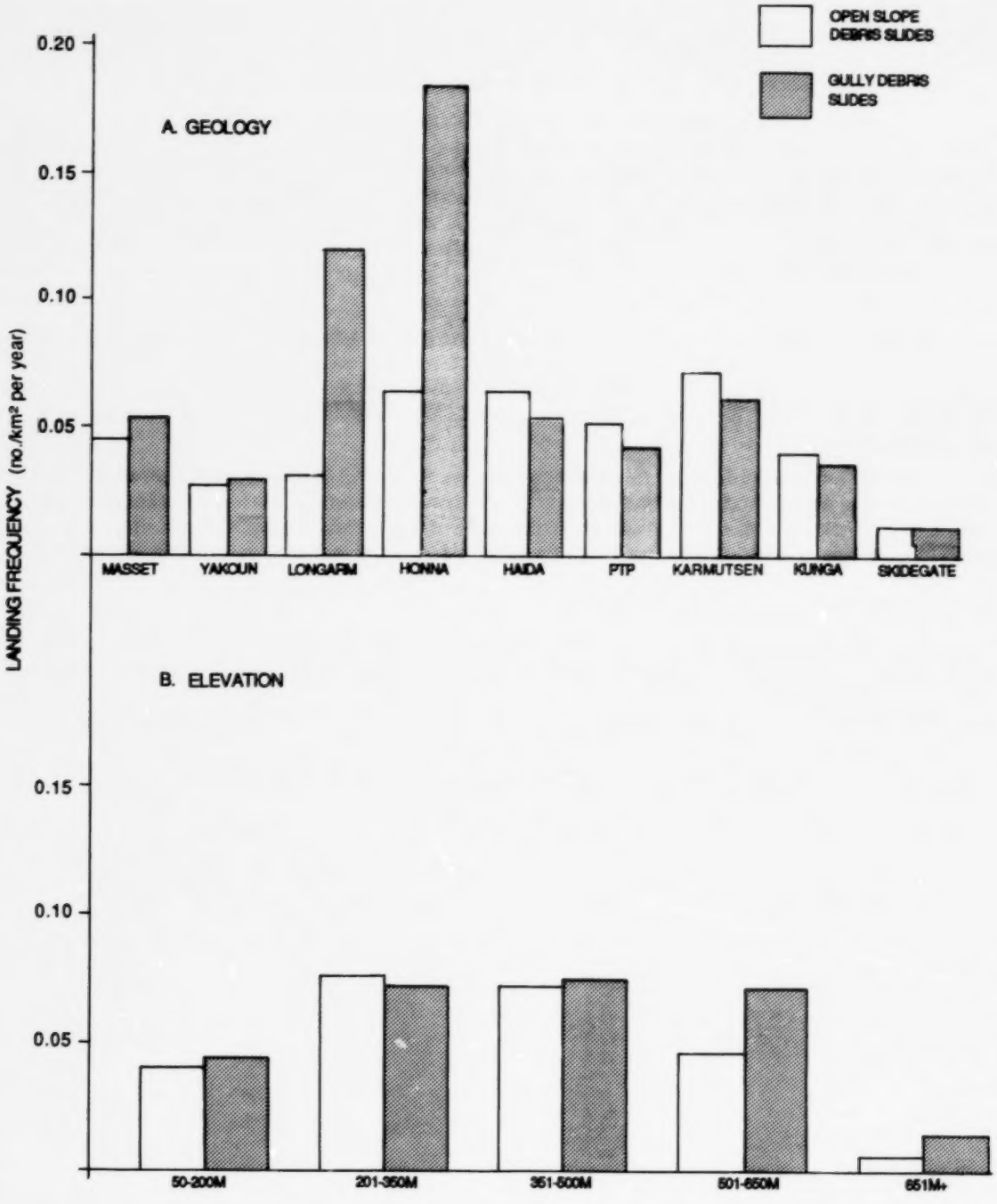


FIGURE 9. The frequency of open slope and gully debris sliding over different geologic formations and elevations in forested terrain.

5.1 Landsliding and the Age of Clearcut Areas

A strong relationship is often observed between landsliding and the time since logging (Sidle *et al.* 1985). Slope stability in response to major storms declines rapidly approximately 5 years after cutting, because of root decay and the consequent loss of support from the root mat. Maximum frequencies of debris sliding in North America usually occur between 3 and 10 years following logging (Megahan *et al.* 1978). In the longer term, as vegetation re-establishes, landslide yield returns to that of the surrounding natural forest.

The open slope debris slides exhibit an interesting behaviour in response to the major storms of 1974 and 1978 (Figure 10A). First, no slides were observed in those areas logged following the 1978 storm. Second, areas clearcut between 1974 and 1978 show landsliding rates that seem nearly independent of age. Finally, a different behaviour is apparent for those areas logged before 1974 and exposed to two major storms. Figure 10A suggests a maximum average response from those areas logged 4 or so years before 1974, with a declining average response for older basins. This pattern is likely confounded by variations in steepness: clearcut areas logged 11 and 12 years before the date of photography lie on Talunkwan Island, an area of particularly steep slopes.

A different behaviour appears in the gully debris slides (Figure 10B). Here, the landslide volume per unit area increases gradually and smoothly with age until 10-12 years. Peak rates observed for 10- to 12-year old clearcut areas may be related to the steep slopes on Talunkwan Island. A moderate landsliding response is observed in gullies logged following 1978, the result of yarding- and deflection-induced landslides, particularly on steep gully walls.

There are several implications to these observations. First, and most important, while there may be a "mean" effect of age on landsliding, extremely wide variation occurs around the trend line because of specific site factors. Second, a consistent data set should include only those clearcuts between 3 and 16 years old. For open slope slides, distinctive behaviour may be observed for areas exposed to one and two major storms.

5.2 Logging Roads, Landslides and Age

Debris sliding from logging roads exhibits relatively little pattern (Table 10). Yields are low in the first 3 years following logging and for ages greater than 13 years, and maximum yields are observed for clearcuts 8-11 years old.

TABLE 10. The variation of average landsliding yields from roads, with age

Years since clearcutting	Road area (ha)	Average debris slide yield (m^3/ha)	Average debris flow yield (m^3/ha)
0	0	0	0
1	6.0	0	0
2	10.4	106	0
3	14.0	363	208
4	23.7	55	0
5	12.6	698	619
6	1.6	375	0
7	6	200	0
8	14.4	764	1743
9	6.1	426	0
11	13	3185[a]	1262
12	2.8	214	0
15	0	0	63
16	0.7	0	0
17	2.4	0	0

[a] Talunkwan Island.

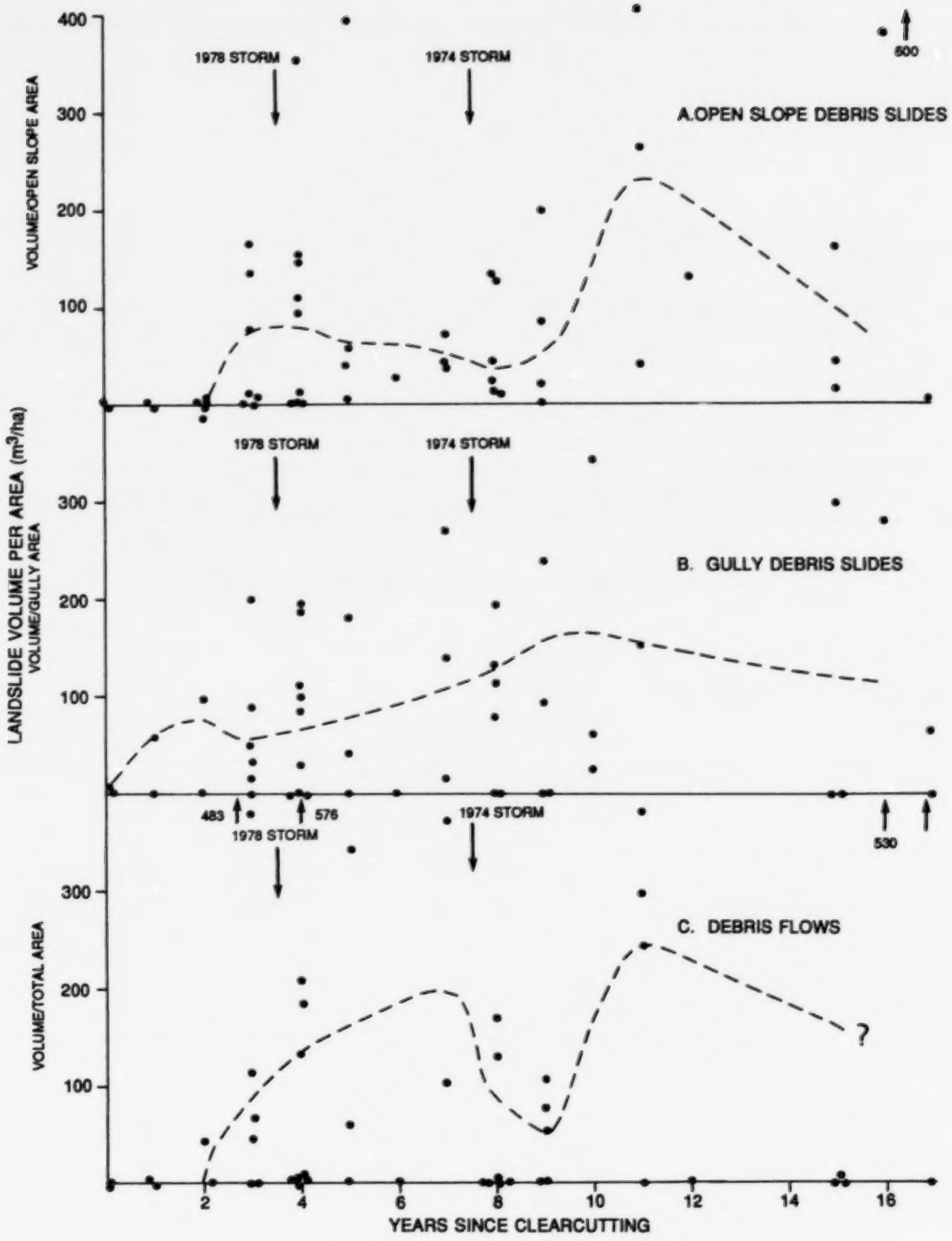


FIGURE 10. Landslide volumes per area for clearcuts of different ages. The dashed lines are drawn through areally weighted averages of the individual years.

The average values are highly variable from year to year and it is difficult to separate the effects of time, site conditions, and different building practices on landsliding yields.

5.3 Landsliding from Open Slope Areas

Open slope landsliding should be affected by the slope, slope shape, and slope position of the individual clearcut areas (Section 6.2). Slope shape and position influence both the frequency and the average size of landsliding.

A moderate relationship exists between average open slope gradient of clearcut and debris slide volume per unit area (Table 11; Figure 11). There is no apparent influence of age or number of storms on these relationships.

The standard error bands on Figure 11 can be used to estimate the variation of the volume per unit area from a given clearcut following a major storm. Areas with average slopes less than 25° exhibit little debris sliding. The inverse regression indicates that at the 95% level, the average slope with zero debris sliding is $23.9 \pm 3.4°$.

Given the highly non-linear relation between debris sliding and slope at a site (Section 6.2), it is perhaps not surprising that only a moderate relationship exists between yield and average patch slope. To account for the distributional aspects of slope, the volume per hectare for each 5° degree slope class based on all open slope debris slides was multiplied by the area occurring in each slope class for each clearcut area. These predicted values were plotted against the observed debris slide volumes (Figure 12). The dominant slope

Table 11. Statistics of regression equations describing debris sliding and debris flows from steepland clearcut areas

Variates		Age (yr)	N	R	a	b_r^a	Se	Range	Significance[b]
Dependent	**Independent**								
Open Slope Environment									
Volume/open area (m^3/ha)	average slope (degrees)	3-7	20	0.51	-620	26.0	80	0-460	0.024*
		8-12	13	0.66	-610	26.0	71	0-412	0.016*
		3-12	33	0.58	-620	26.1	75	0-460	.001*
Gully Headwall Environment									
Volume/headwall area (m^3/ha)	average slope (degrees)	3-7	15	0.26	-213	9.2	83	0-267	0.10
		9-16	11	0.54	-363	16.4	77	0-600	0.089
		3-16	26	0.36	-284	12.4	97	0-600	0.038*
Volume/total area per year (m^3/ha per year)	proportion of clearcut in gully	3-16	26	0.61	-1.6	15.8	4.1	0-18.9	0.0*
Gully Sidewall Environment									
Volume/sidewall area (m^3/ha per year)	average slope (degrees)	3-16	28	0.30	-176	7.8	141	0-500	0.121
Volume/total area per year (m^3/ha per year)	gully density (km/ha)	3-16	28	0.66	-1.7	0.81	3.2	0-19.4	0.0*
Debris Flows									
Volume/area (m^3/ha)	proportion of clearcut in gully	3-16	31	0.53	-65	558	125	0-530	0.004*
		TOP SLOPES	18	0.77	-114	840	77	0-530	0.0*
Volume/area (m^3/ha)	no. headwall per area (no./ha)	3-16	32	0.57	43.8	788	115	0-530	0.0*

[a] Functional slopes were not calculated because of the difficulty of estimating λ. Most of the error lies in "the dependent variable," from estimating slide volumes. The regression slopes should be a reasonable estimate of the functional slope.

[b] Asterisks show those relationships significant at 0.05.

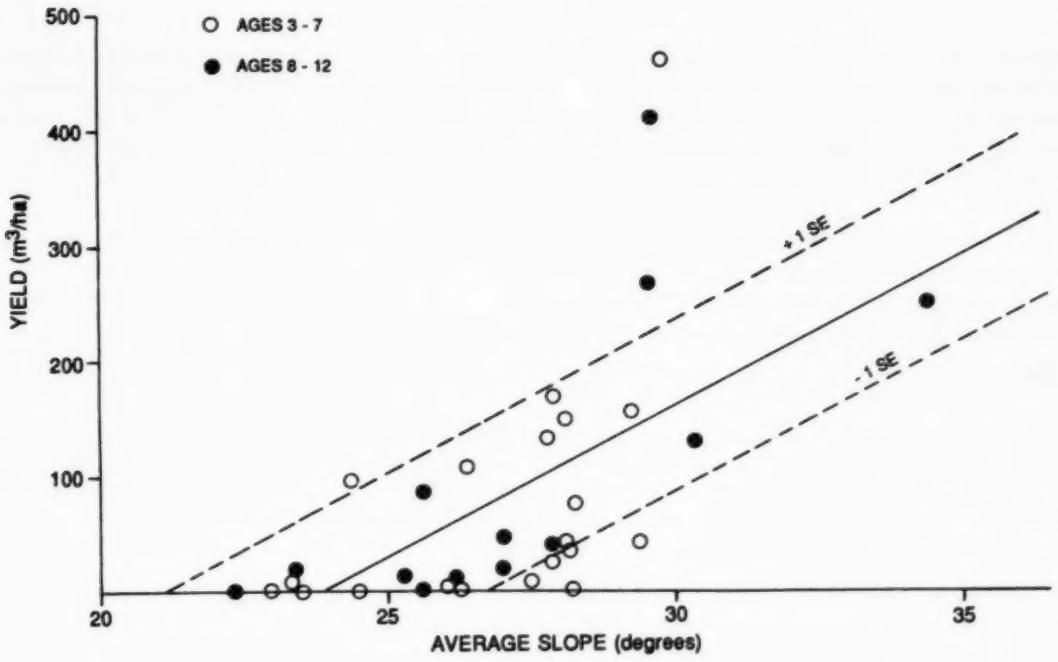


FIGURE 11. The relationship between yield and average slope for the open slope portion of clearcut areas.

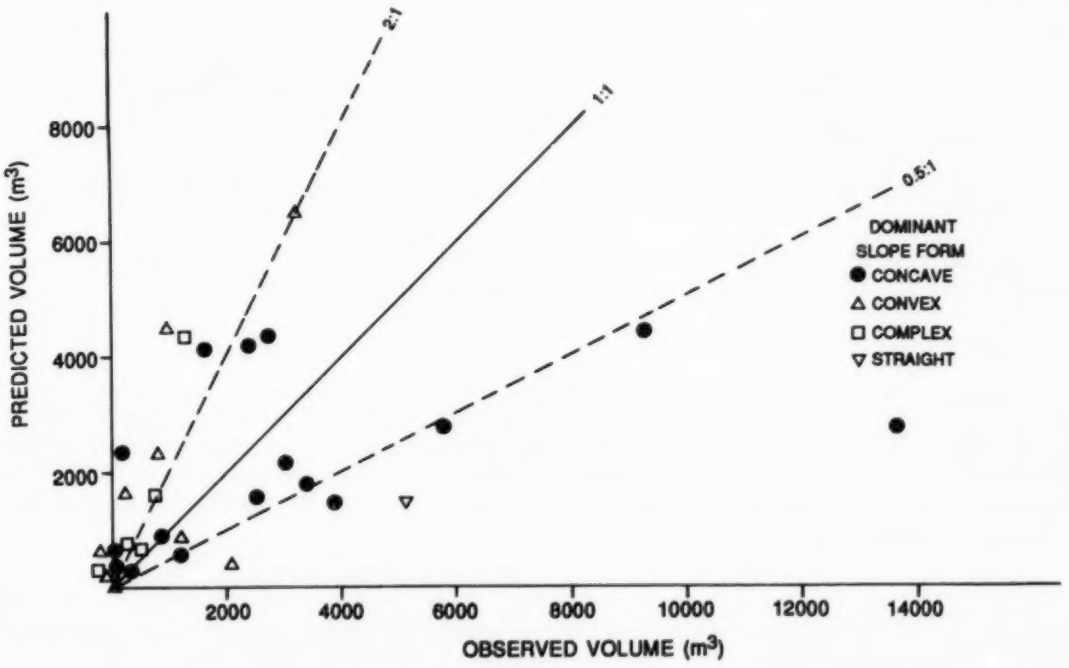


FIGURE 12. Observed versus predicted debris slide volumes for the open slope portion of clearcut areas. Predicted volumes are based on the distribution of slope angles in each clearcut area.

shape of the clearcuts was characterized from the grid sample data (the slope shape with the greatest number of observations was assumed to be the dominant type). There is a tendency for under-estimation of observed values for patches dominated by concave slopes and over-estimation for convex slopes. This is the expected result (see Figure 20) and the magnitudes are approximately correct. The concave-shaped patches fall at approximately twice the average magnitude and the convex-shaped patches at approximately one-half this value.

So far, linear regressions between average slope and landslide yield have been tested. These are useful for demonstrating relationships and for predicting mean landsliding response. In circumstances where maximum rates or worst-case situations are of concern, it may be more appropriate to draw an envelope around the sample data on Figures 11 and 13.

5.4 Landsliding from Gully Headwalls

The debris sliding frequency from gully headwalls should be influenced by the slope, slope shape, and position of the individual clearcut areas (Section 6.2). These variables should be related to the volume per unit area of landsliding: Figure 10B and Table 11 suggest that landsliding yields and volumes are approximately independent of age or only weakly dependent on it. Figure 13 includes those areas between 3 and 16 years of age. Thirteen of the clearcut areas include no gully headwall.

Average gully headwall gradient has a significant but very weak relation to landslide yield, suggesting that other factors assume a dominant role. There also appears to be some difference between the relationships for those areas of 3 - 7 years and those between 8 and 16 years. The greater variability and greater number of zero observations in the younger clearcuts suggest a vague relationship between storm patterns and gully headwall sliding.

The distributional aspects of slope also influence gully headwall sliding (Figure 14). As for the open slope slides, the overall volume per hectare for each slope class was used to predict the total volume of failure for each clearcut. Failure rates are differentiated by slope position. Upper slopes are over-predicted, mid- and bottom slopes are under-predicted. This corresponds to the variation of frequencies with slope position described in Chapter 6 (Figure 20). It is unclear why lower slopes are more susceptible to failure, unless the reason is related to distribution of water along the slope profile, or to differences in surficial material.

5.5 Landsliding from Gully Sidewalls

Gully sidewall sliding should be related principally to elevation (Section 6.2). No relation is observed with average slope angle (Table 11).

A weak relation occurs between the gully sidewall sliding per total steepland area per year and the density of gullies (Table 11). This is likely a result of the particular clearcut areas sampled.

5.6 Debris Flows from Clearcut Areas

In clearcuts, debris flows are primarily triggered by gully headwall slides (65%) and secondarily by gully sidewall slides (16%) and open slides (12%). Overall, about one debris flow occurs for every 3.2 gully slides in clearcut areas, and one flow occurs for every 3.3 gully slides in forested terrain. The increased incidence of flows in clearcut areas is simply due to an increased number of triggers. Conditions vary in the individual sites, but there appears to be a a relationship between flow volume per unit area and the failure rate of headwalls for the individual clearcuts (Table 11; Figure 15).

An interesting relationship occurs between the proportion of gully in an individual clearcut and the debris flow yields (Figure 16). Despite the greater susceptibility of mid- and bottom slope sites to headwall failure, these sites are relatively unsuccessful in producing debris flows. Flows primarily initiate on upper slopes and the ratio of slides to flows in these areas is much less than 3:1.

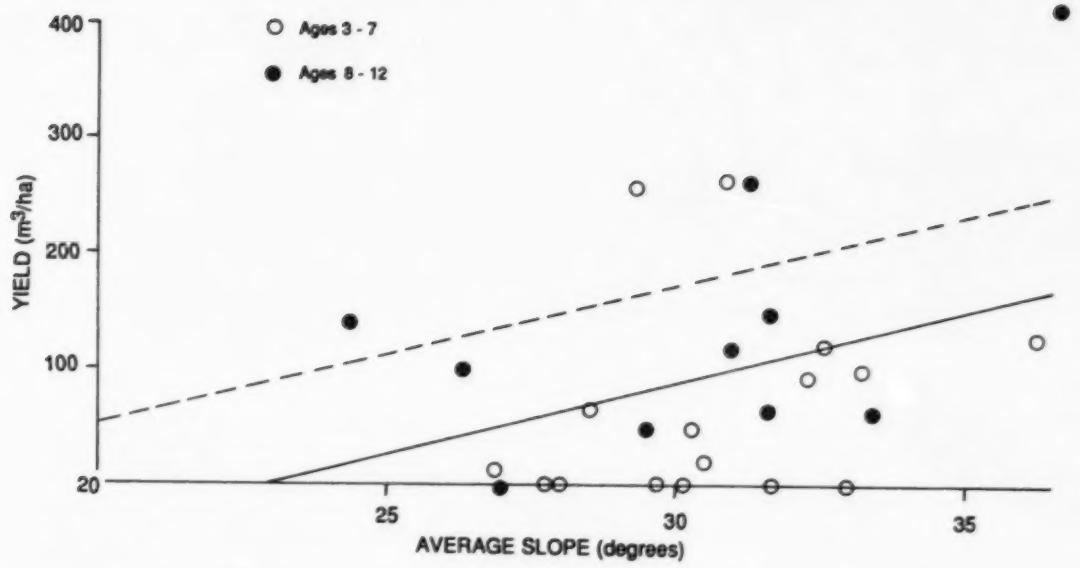


FIGURE 13. The relationship between yield and average slope for the gully headwall portion of clearcut areas.

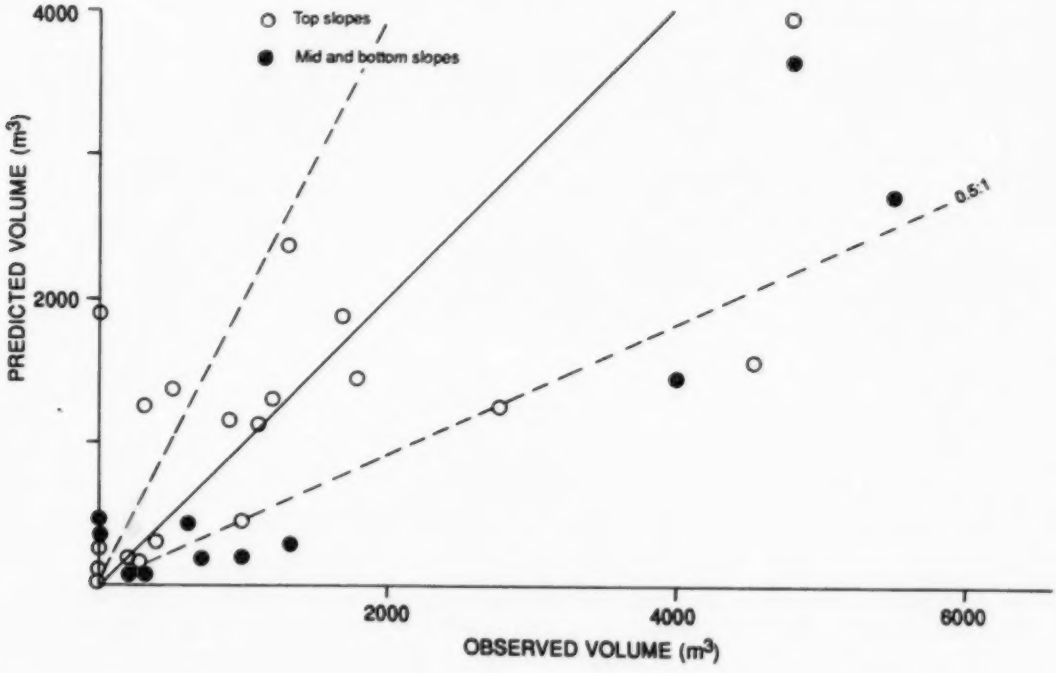


FIGURE 14. Observed versus predicted slide volumes for the headwall portions of clearcut areas. Predicted volumes are based on the distribution of slope angles in each clearcut area.

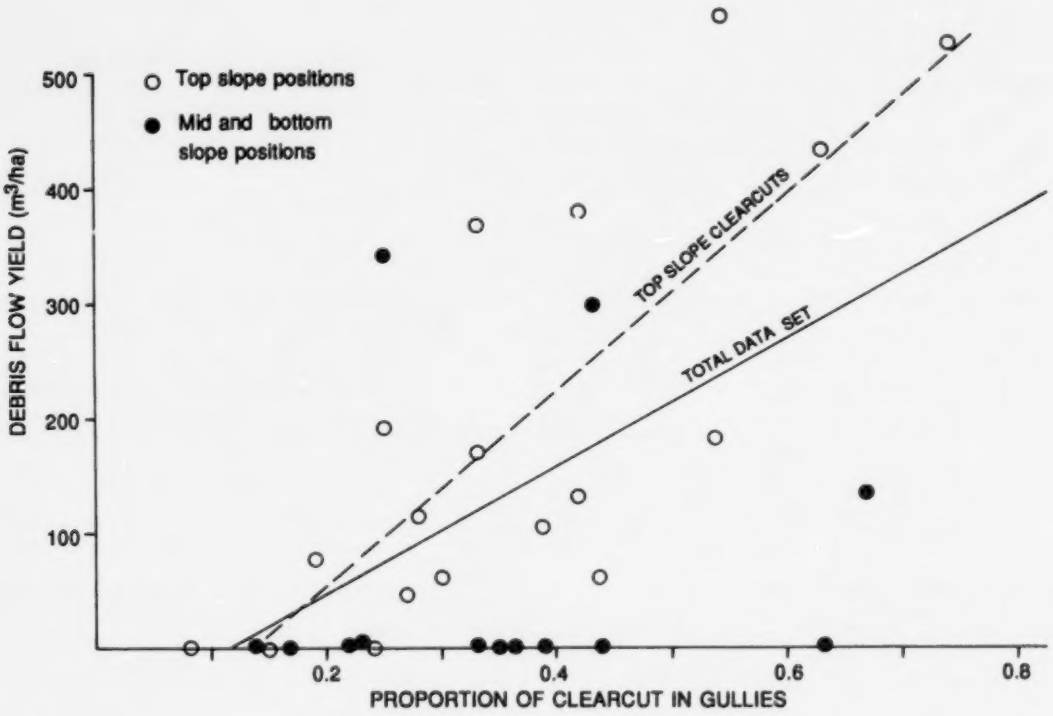


FIGURE 15. The relationship between debris flow yield (m³/ha) and the proportion of the clearcut area in gullies.

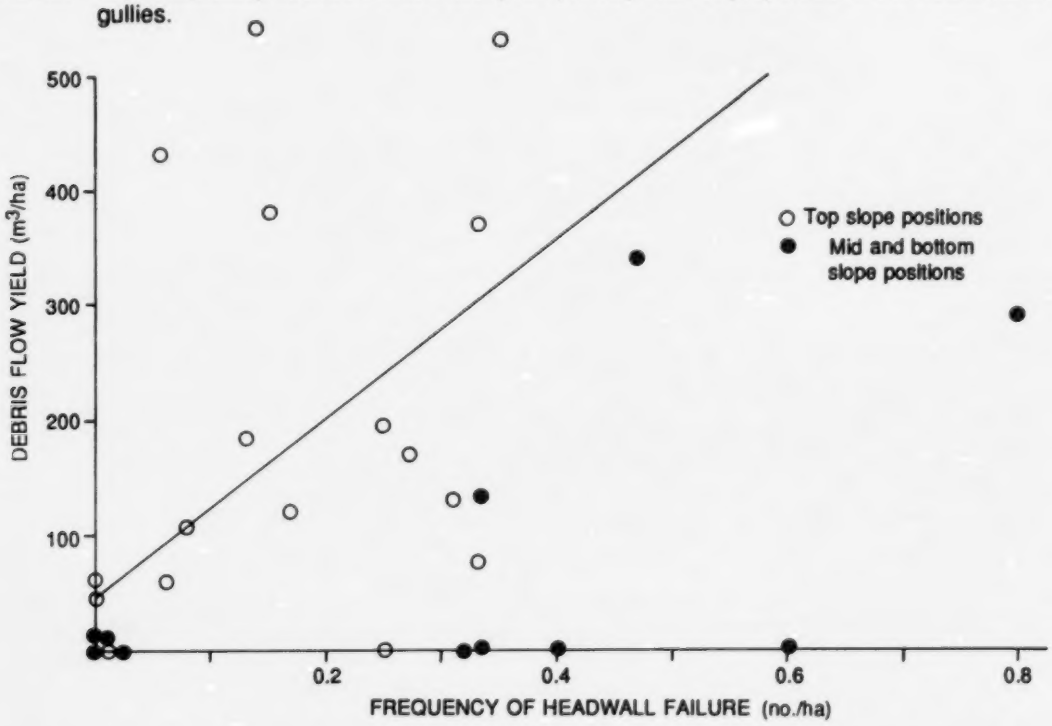


FIGURE 16. The relationship between debris flow yield (m³/ha) and the frequency of headwall failure.

5.7 Landslides Entering Streams

The volume of landslide debris directly entering streams depends on the factors affecting the rate of landsliding, the size of the landslides, and the general character of the terrain lying between the clearcut area and a stream. Unlike in forested terrain, most of the volume entering streams from clearcuts is delivered by debris flows (Rood 1984). These are significant because of the large volume involved in each event: average sizes are near 6000 m^3 and large events range to 30 000 m^3.

One important factor in clearcut areas is the interception of flows by road fills. Approximately 20% of the flows initiating on upper slopes are "caught" by mid-slope roads.

Runout slope is defined as the angle between the bottom of the initiation zone and the top of the deposition zone and, in essence, measures the average land surface slope traversed by a landslide. Slides and flows have different characteristic distributions of runout slopes (Figure 17). Average runout slopes for open slope and gully headwall slides are 29° and maximum slopes are more than 40°; debris flows exhibit average runout slopes of 23°. The issue is complicated by weak positive correlations between runout slopes and landslide size, particularly for debris flows. Larger flows are related to lower runout slopes and an increased probability of entering streams.

Figure 17 also shows the distribution of slopes between the clearcut patches and the closest stream. By comparing the typical slopes that must be traversed to reach a stream with the distribution of runout slopes it is obvious that debris slides would enter streams only under relatively unusual circumstances. Only the largest debris slides or those initiating on steep lower valley walls near the stream are likely to enter the channel.

It is also apparent that if a debris flow initiates, it has some probability of entering a stream in clearcut patches with slopes to streams exceeding 10° (Table 12). The probability increases with an increasing angle between the clearcut patch and the stream. Results in Table 12 are similar to the rule of thumb that flows maintain momentum above 15°, tend to lose momentum on slopes down to 10°, and stop on slopes of 8-12° (Hungr *et al.* 1984). The analysis in Table 12 takes no account of the potential or actual debris flow frequency within the clearcut areas and this, in part, affects the interclass variability. As well, the slope profile may exert some influence on stream entry.

While the number of clearcut areas with landslides entering streams is too small for statistical analysis, it is possible to identify those landscape characteristics that contribute to large volumes entering streams.

TABLE 12. Yield to streams and the angle between the clearcut area and the stream

Slope class	Yield to streams (m^3/ha) (debris flows and slides)	Proportion of flows entering streams
0-3	0	0
4-6	0	0
7-9	0	0
10-12	33	0.27
13-15	63	0.62
16-18	78	1.0
19-21	307	1.0
22-24	112	1.0

Problems are particularly apparent for sites involving logging on upper gullied slopes of small (second- and third-order) drainage basins. Upper slope positions have steeper slopes and a higher proportion of gully headwall area. Building roads across the gully headwalls accelerates the rate of debris slide initiation. In these situations, the sites are often directly connected to the drainage net over slopes of 15° or greater. These sites promote a greater incidence of debris slides, providing the necessary triggers for debris flows, as well as the steep runout slopes where the probability of stream entry exceeds 30%.

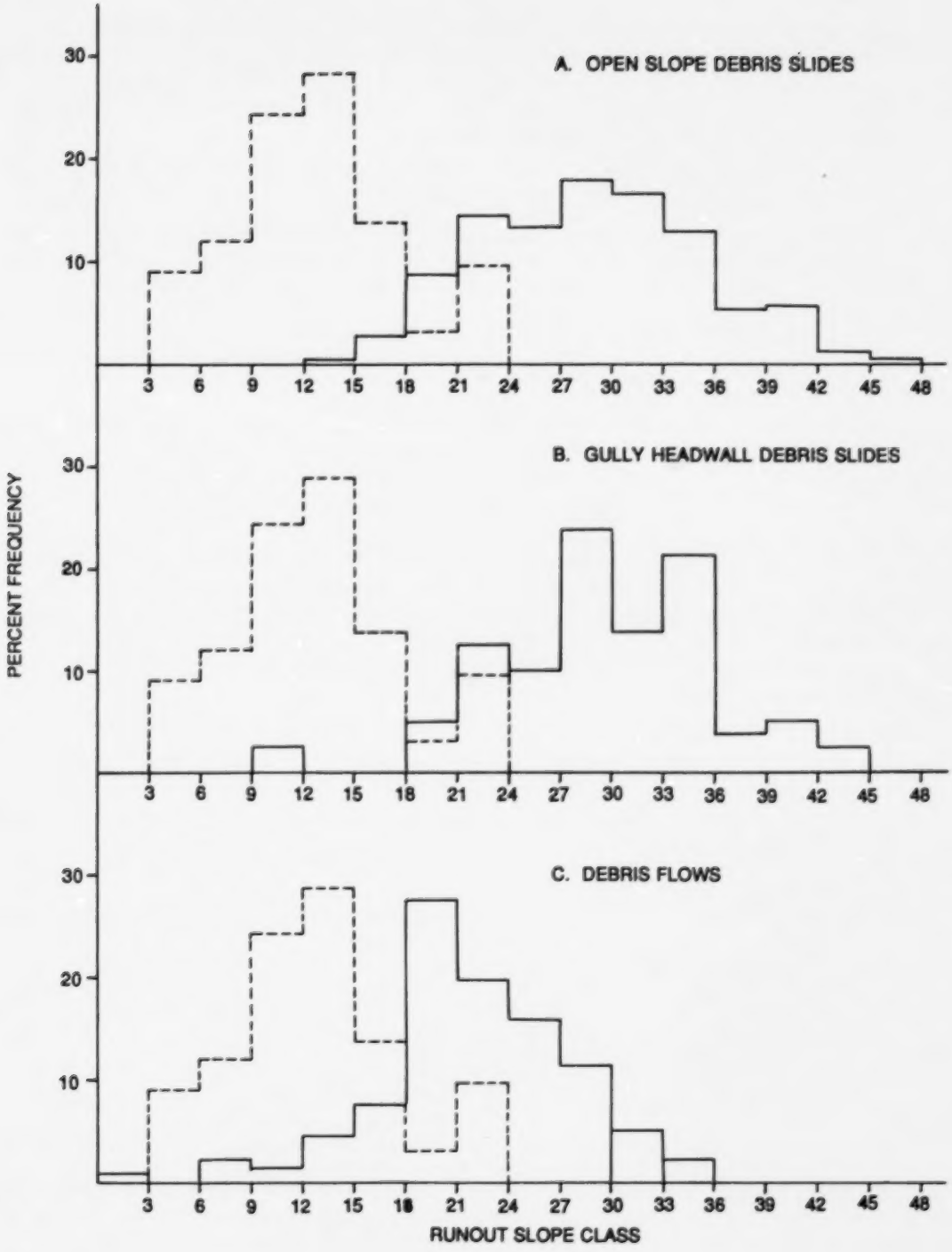

A. OPEN SLOPE DEBRIS SLIDES
B. GULLY HEADWALL DEBRIS SLIDES
C. DEBRIS FLOWS
PERCENT FREQUENCY
RUNOUT SLOPE CLASS
30
20
10
3 6 9 12 15 18 21 24 27 30 33 36 39 42 45 48

FIGURE 17. Average runout slope distributions for debris slides and debris flows. The dashed lines show the distribution of slopes leading from the clearcut areas to streams.

6 SITE CHARACTERISTICS AND LANDSLIDING IN CLEARCUT TERRAIN

The advantage of coupling a landslide inventory with landscape sampling is that frequency of failure can be compared for different site characteristics, thereby eliminating many of the analytic and interpretive difficulties described in Chapter 4.

Statistical testing for relationships is straightforward. If a particular variate has no effect on landsliding rates, then equal frequencies of landsliding would be expected in each category. Under this condition, the expected number of landslides in each category of a chi-square test was calculated directly from the portion of the total sample area with that characteristic.

The age distribution of the terrain was also considered. Adjustment to the data set included elimination of terrain logged less than 3 years before and more than 16 years after the date of photography. No adjustment was made for the effects of varying slope on landsliding rates. This is obviously a vexing question: both average slope and slope distribution are related to landsliding rates and confound the effects of other variables.

6.1 Landscape Position

This report has emphasized that open slope, gully headwall, and gully sidewall sites provide very different controls over landsliding and should be examined separately (Table 13).

TABLE 13. Basic characteristics of open, gully headwall, and gully sidewall clearcut terrain

Landscape	Area (ha)	Failure[a,b] frequency (no./km² per year)	Dominant slope type	Average slope (degrees)
Open	1035	2.0	concave/convex	27.5
Gully headwall	356	3.2	concave	31.0
Gully sidewall[c]	291	2.6	-	38.4

[a] Converted to a frequency with the weighted average age (8 years) of the clearcut areas.
[b] Gully failure frequencies are significantly greater than open slope failure frequencies at p = 0.01.
[c] Does not include active wall slides. There are 28 additional active wall failures, raising the frequency to 3.7/km² per year.

Gully headwalls and sidewalls are characteristically over-steepened compared to open terrain because it is at these sites that the incised gully rejoins the open slope.

6.2 Site Characteristics

Each of the landscape positions exhibits a different set of site characteristics that controls landsliding (Table 14; Figures 18-20). The relation between slope and failure frequency is particularly interesting. In open slope areas, a non-linear increase in failure frequency is observed with increasing slope. Failure rates are especially accelerated for slopes exceeding 35°, where this angle corresponds roughly to typical angles of internal friction for non-cohesive soils as measured by other authors (Swanston 1974; Ballard and Willington 1975). A similar increase of frequency with slope is observed for the gully headwall slides except that the onset of accelerated response seems delayed to slopes exceeding 40°.

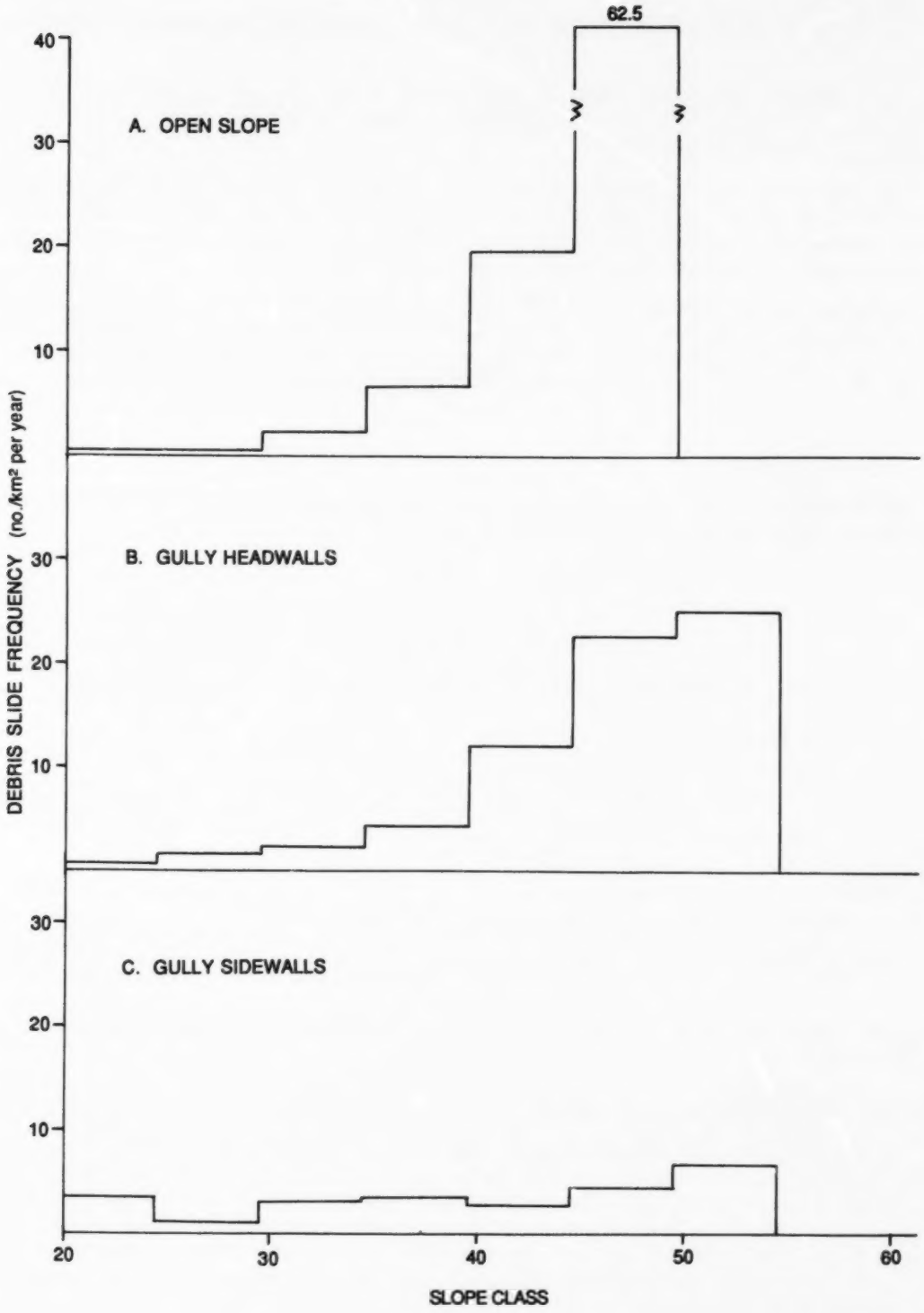


FIGURE 18. The variation of the frequency of debris sliding with slope in clearcut areas, Queen Charlotte Islands.

The gully sidewall slides differ. Failure frequency is independent of slope angle above angles of 20° (Figure 19). An engineering analysis of gully landsliding (Krag *et al.* 1986) identified yarding disturbance and subsurface seepage on spring lines as important factors in slide initiation. These seem to be dominant factors explaining failure in an environment where all slopes are over-steepened and the average slope angle exceeds the typical internal angle of friction.

In the open slope environment, form and position also influence landsliding frequency (Figure 20). There are relatively few failures on convex slopes and in bottom-slope positions. Krag *et al.* (1986) associated open slope landsliding with major changes in slope angle (i.e., concave, convex or complex sites). This is certainly reflected in the landslide totals, but nearly equivalent frequencies are observed for straight and non-straight slope forms. In any event, maximum frequency variation from these parameters amounts to a factor of only 2, while there is a 100 times variation associated with the slope classes.

Gully headwall slide frequency responds to slope shape, position, and elevation. Position and elevation describe the same behaviour — higher frequencies at slope bottoms and lower elevations — and have a marked effect (4 times variation) on frequencies. This occurrence is particularly interesting because approximately 70% of the headwall area occurs on upper-slope positions. Gully headwalls on mid- and lower slopes are associated with major slope breaks or benches (MacMillan Creek, Bonanza Creek) with convex slopes below. Despite being a relatively rare circumstance, these positions exhibit high rates of failure, possibly because they receive and concentrate groundwater from upslope. Surficial material may also be an important factor.

Slope form also affects landsliding in gully headwalls. Concave slopes exhibit the highest rates of failure, and over 50% of the headwall sites were described as concave. Krag *et al.* (1986) described the concave headwalls as receiving sites, noted the presence of springlines or seepages and associated concave headwalls with linear depressions. Convex slopes typically exhibit lower slope angles and lower rates of failure.

Only a limited set of variables is available to describe sliding along sidewalls. Sidewalls exhibit behaviour, with elevation, opposite to that of headwalls. For sidewalls, the maximum frequencies are observed on the relatively few sites occurring in upper elevations or on the tops of slopes.

TABLE 14. Chi-square statistics for the relation between site characteristics and the number of debris slides. The null hypothesis is that there is an equal landslide frequency per hectare

Variable	No. Categories	No. Slides	X^2	Significance[a]
Open slopes				
Slope	7	165	829.4	0.0*
Elevation	4	165	1.7	0.64
Aspect	8	165	14.0	0.052
Slope form	4	165	19.7	.001*
Slope position	3	165	12.4	.003*
Geology[b]	5	165	23.6	.001*
Gully headwalls				
Slope	7	92	142.7	0.0*
Elevation	4	92	32.1	.001*
Aspect	8	92	13.7	.059
Slope form	4	92	13.3	.005*
Slope position	3	92	25.0	.001*
Geology[b]	5	92	6.3	.183
Gully sidewalls				
Slope	7	60	10.3	.117
Elevation	4	60	50.0	0.0*
Geology[b]	5	60	7.4	0.121

[a] Asterisks refer to those relationships where the null hypothesis is rejected (p=0.01).
[b] Includes Masset, Yakoun, Karmutsen, Post Tectonic Plutons, and Sedimentary (Honna and Haida) formations (Sutherland Brown 1968). See discussion in Section 5.1.

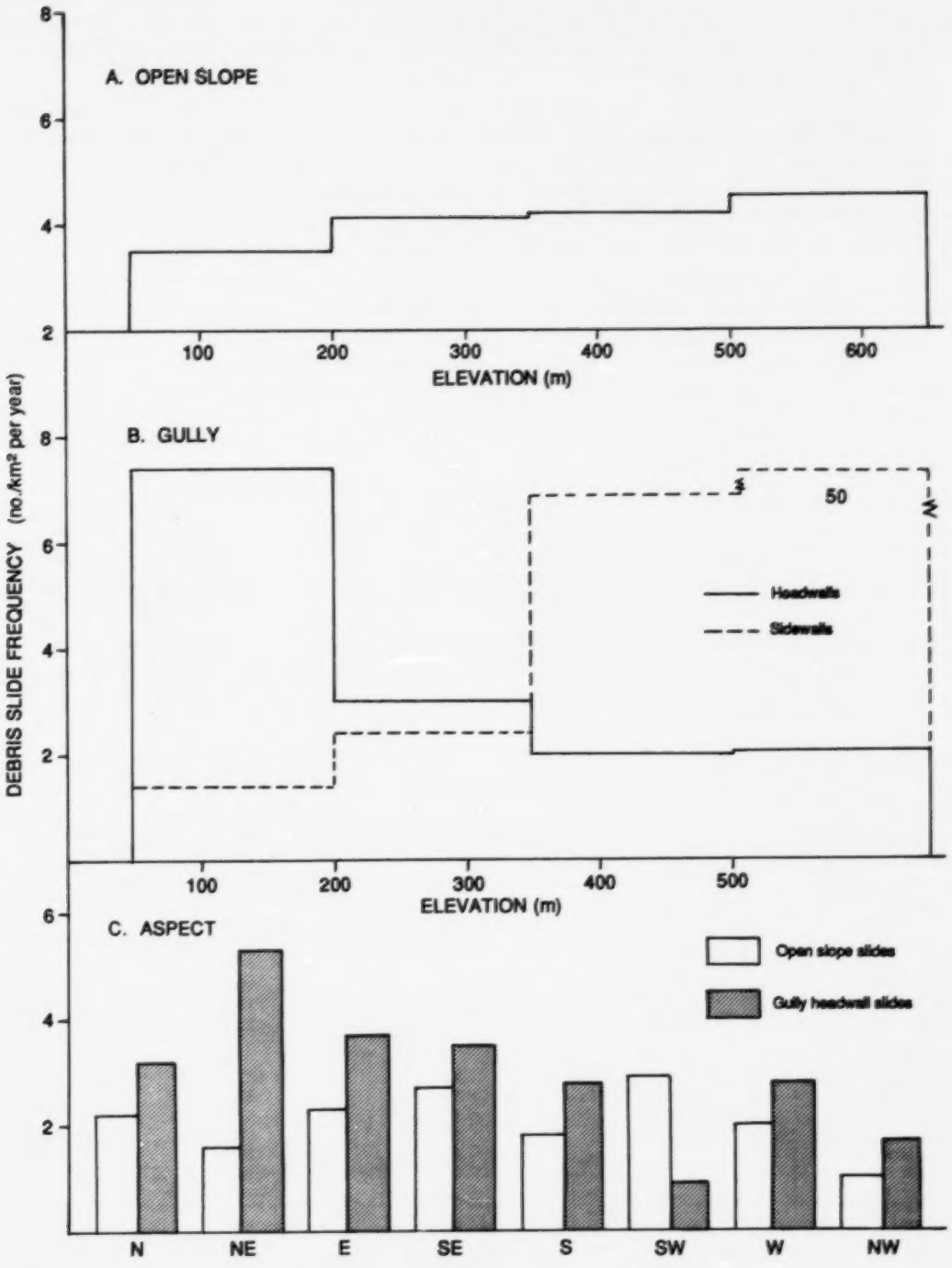


FIGURE 19. The variation of the frequency of debris sliding with elevation and aspect in clearcut areas, Queen Charlotte Islands.

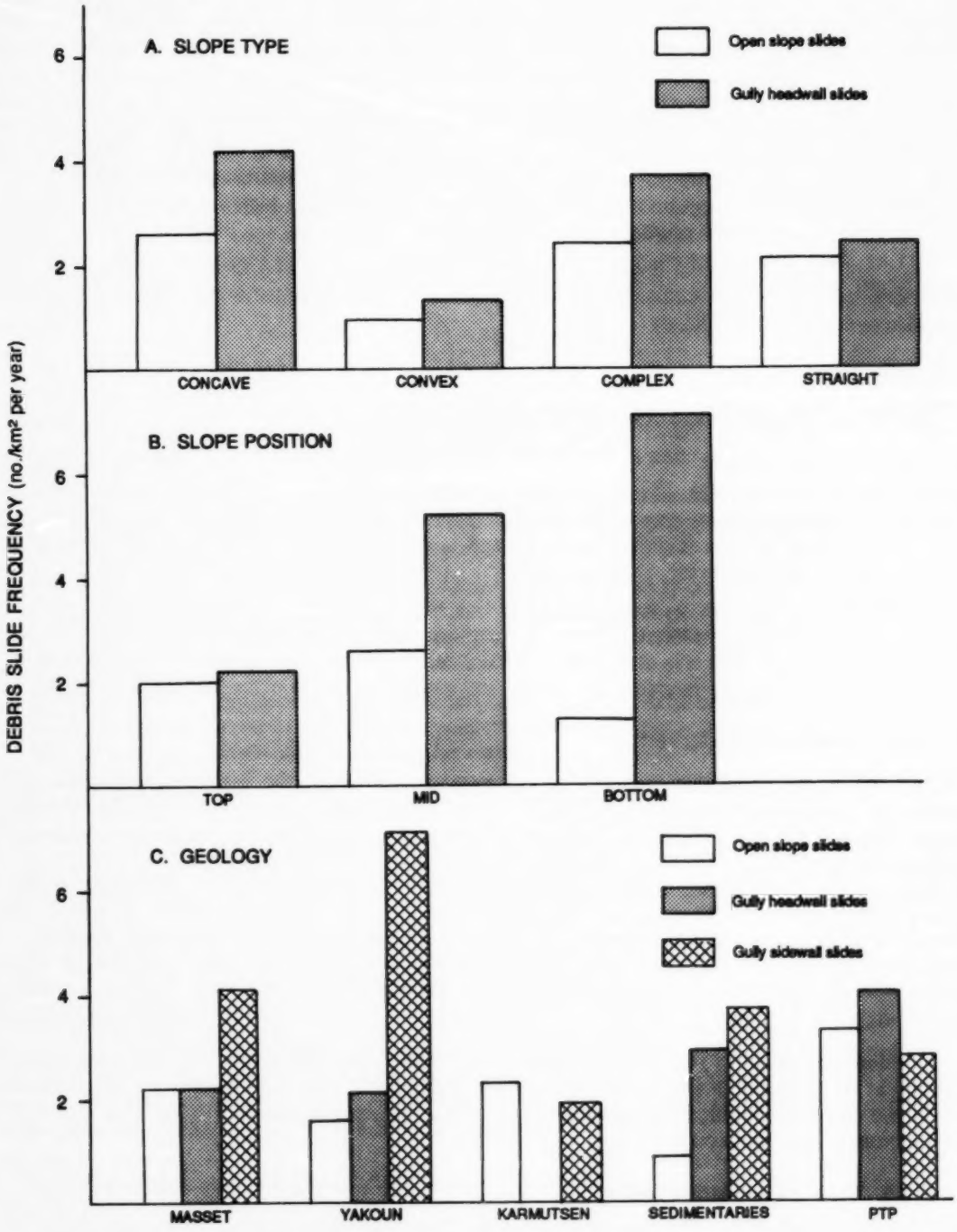


FIGURE 20. The variation of the frequency of debris sliding with slope form, slope position, and bedrock formation.

7 CONCLUSIONS

On a regional level, it is often assumed that control of the volume and frequency of landsliding is exerted by variation in geology, physiography, and climate. These factors seem to play only a limited role on the Queen Charlotte Islands. Bedrock formation (mapped at 1:125 000; Sutherland Brown 1968) plays no significant role in determining regional variations in landsliding volume or frequency from steeplands, nor does gross regional physiography. Mean annual precipitation, however, representing other parameters such as the magnitude of the 24-hour storm, does influence landsliding frequency: the highest rates of failure occur in the high mean annual precipitation zone along the west coast of the Queen Charlotte Islands (Gimbarzevsky 1988). The difference between the highest and lowest frequencies was less than a factor of two. Of course, climatic factors are closely bound with physiography.

Since only limited regional control is exerted over landsliding in the Queen Charlotte Islands, the conclusions concerning site characteristics and landsliding drawn from the data set in this report are applicable over most of the Islands.

7.1 Landslide Magnitude

The average or median size of landslides is controlled by the following factors:

- landslide type: debris flows average 5-10 times as much volume as debris slides.
- location: the magnitude of events is strongly influenced by location, whether forested open slope, forested gully, clearcut open slope, or clearcut gully. Forested open slope debris slides are approximately twice as large as clearcut open slope slides. Forested gully failures average 1.5 times as large as clearcut gully failures.
- site conditions: in forested and clearcut terrain, the magnitude of landslides is influenced by slope shape and slope position. Larger slides originate on upper slope positions and on concave and complex slopes. The size distribution of landslides is influenced by slope position. The volume of a landslide is primarily related to its length, and longer slides can occur from upper slope positions.

7.2 Landsliding in Forested Terrain

The role of site conditions in determining frequencies of landsliding was examined indirectly from numbers of landslides in forested terrain. The number of landslides associated with different site conditions was determined by both the frequency of failure and the total area covered by those conditions. In forested terrain, slope was found to influence the frequency of landsliding: the majority (80%) of open slope slides initiated on slopes steeper than 35°. Aspect plays no role in influencing landslides. With slope position and slope shape, it is not possible to separate the effect of variations in area and variations in frequency on the numbers of failures. Examination of the clearcut areas suggests that, in the case of slope shape, areal variations in steepland area among the different categories may be as significant as variations in frequency.

7.3 Landsliding in Clearcut Terrain

An interesting result is that clearcut debris sliding rates are independent of the numbers of storms occurring at the site and of the age of the site at the time of the storm for the pattern observed over the study area. At the very least, average age dependence is dominated by site conditions in the sample and is of much less importance than these conditions.

7.3.1 Open slope debris sliding

Slope is the dominant variable influencing open slope debris sliding. The role of this variable and its effectiveness in controlling landsliding changes as scale increases from the site to the basin. At the site, the relation is highly non-linear, and steeper slopes (above 35°) dominate the frequency and total volume of landsliding.

For an individual clearcut area, average slope provides only a moderate level of explanation of landsliding. This is due, in large part, to the distribution of slopes within the clearcut areas. Even though clearcut open slopes typically average only 25-30°, the proportion of area exceeding 35° ranges from 0 to 50%. These steeper slopes control the landsliding. Other factors also control landsliding. Concave slopes exhibit greater landsliding rates than convex; upper slopes also exhibit greater rates. Both these factors also influence yield by increasing the average or median size of open slope landslides.

Finally, slope is a necessary, but not a sufficient condition for landsliding. For average slopes ranging to 28°, some sites exhibit zero rates of failure. In the clearcut environment, time may exert some control over this behaviour.

At the next level of integration — the drainage basin — slope is the dominant factor explaining open slope landsliding. For these larger units, the distribution aspects of landsliding are more closely tied to average slope. Obvious exceptions occur, particularly for the steepest basins, such as Mosquito Tributary and Mountain Creek. It is assumed that these exceptions are due to their particular soil conditions.

7.3.2 Gully debris sliding

Different factors are important in controlling initiation of landslides in gullies. Gully headwalls and sidewalls are over-steepened compared to open slopes, but for headwalls average slopes are only moderately steeper than surrounding open terrain.

The terrain type affects site relations between slope and debris sliding. In the steeper sidewall environment, slope variations are unimportant and failure is controlled by yarding and deflection scarring and the location of seepage zones and springlines.

At a site, headwall failure rates exhibit a similar relation to slope as do open slope failure rates. The primary difference is that the point where failure rate rapidly increases with slope is shifted to steeper slopes. Failure rates in the headwall environment appear more sensitive to such factors as slope form and position which, in part, control the distribution of soil moisture.

At the level of integration of a clearcut, only weak relations exist between headwall sliding and average slope. This seems to be due to the role of moisture distribution, particularly as reflected in slope position, and the particular distribution of slope elements.

7.3.3 Debris flows

Only weak relations are described at the level of the drainage basin, primarily because in the difficulty of accounting for variations in the proportion and density in gullies in individual basins from medium scale maps.

Debris flows and the volume of material entering streams are intimately related in clearcut areas. Flows are primarily triggered by headwall failures and are particularly triggered by upper slope headwall slides. Those sites encouraging upper slope headwall slides (steep slopes, high road fills, concave slopes) also experience high numbers of debris flows.

Entry into a stream depends on the landscape between the clearcut and the stream, as well as on the factors initiating debris flows. There seems to be a critical angle of approximately 10° below which flows less easily pass into a stream. Distance may also be important, but is difficult to separate from the more important effect of slope without a much larger data set.

7.3.4 Site characteristics and landsliding

One of the most interesting results of this study is the weak correlation between landslide frequency and some of the gross site characteristics identifiable from aerial photographs and maps. Similarly, on Vancouver Island, Rollerson (1984) found no relationship between clearcut landsliding frequency and

aspect or bedrock type. In Hawkes Bay, New Zealand, an area of extensive debris avalanching, there is little apparent relationship between failure, slope position, plan or profile slope shape, or distance from the ridgeline. Although several explanations are possible, the most likely lies in the conditions which produce the high intensity of episodic mass wasting in the Queen Charlotte Islands. Average yields and frequencies of landsliding, particularly from clearcut, range from 5 to 20 times as large as those in other Pacific Northwest regions (Rood 1984). Site conditions suitable for debris sliding for a given slope occur not just in a few particularly susceptible locations, but over most of the land in this class. This is particularly true for clearcut slopes exceeding 35°, where failure rates are near one for every 2 ha. As a result, landsliding occurs equally over the gross physiographic variables describing site conditions, and is primarily affected by variations in slope angle.

7.4 Implications for Prediction of Landsliding

Landsliding, at an individual point, occurs because of a complex set of interactions between storm characteristics, site hydrology, soil properties, vegetation, and the physiography of the hillside. Many variables that are directly pertinent to failure are difficult or expensive to measure, or highly variable in space or time. Ideally, variables used for prediction of debris sliding should:

- clearly separate sites of low magnitude or frequency of landsliding from those of high magnitude or frequency of landsliding;
- be easily extracted from air photographs or topographic maps; and
- be geomorphologically meaningful.

Thus, slope and slope shape appear to be the most useful variables measured in this study.

Open slope failures come primarily from a relatively small and steep portion of an overall lower gradient site. The importance of these failures lies in their effect on downslope site productivity (Smith *et al.* 1986): an average of 13 ha/km^2 are affected by debris sliding in clearcut steeplands (Rood 1984). Open slope slides seldom enter streams. One exception lies in the larger failures which directly enter either streams or enter gullies, liquefy, and travel to streams as debris flows. Unfortunately, the conditions promoting larger slides are only poorly understood - upper slope concave sites seem most susceptible, though these sites include a large part of the landscape.

Gully headwalls provide a key link between clearcutting, debris flows, and the volume of material entering streams. Headwall failures dominate in initiating debris flows and certain sites are particularly susceptible. The steep upper concave slopes of first- and second-order basins not only provide conditions to initiate debris slides, but are often connected to the mainstream by slopes that all but ensure flows will enter reaches that are of particular value to fisheries. Time, weather patterns, and the probabilistic element of debris sliding also influence this process. However, control of these failures requires careful treatment of headwall sites, particularly in road location and yarding patterns.

Still, the study indicates that the gross site conditions observed on medium-scale air photographs are not sufficiently related to landsliding such that relative slope stability can be predicted or mapped following clearcut logging. These results are pertinent to the design of further investigations. Many variables that are often assumed to influence landsliding — bedrock formation, physiographic region, aspect — appear to be unimportant in the Queen Charlotte Islands. Future studies should ignore these variables and concentrate on describing the landscape at finer levels of integration.

8 REFERENCES

Alley, N. and B. Thomson. 1978. Aspects of environmental geology, parts of Graham Island, Queen Charlotte Islands. B.C. Min. Environ., Resource Anal. Branch. Bull. No. 2. 65 p.

Ballard, T. and R. Willington. 1975. Slope instability in relation to timber harvesting in the Chilliwack Provincial Forest. The Forestry Chronicle 51:59-62.

Blalock, H.M. 1972. Social statistics. McGraw-Hill, New York, N.Y. 583 p.

Chatwin, S. and T. Rollerson. 1983. Landslide study: TFL 39, Block 6. Woodland Services Division. MacMillan Bloedel Ltd., Nanaimo, B.C. 18 p. and appendices.

Church, M. 1983. Concepts of sediment transfer and transport in the Queen Charlotte Islands. B.C. Min. For. and Min. Environ., Fish/Forestry Interaction Program. Working Paper No. 2. 23 p.

Gimbarzevsky, P. 1988. Mass wasting in the Queen Charlotte Islands; a regional inventory. B.C. Min. For., Land. Manage. Rep. 29. 96 p.

Holland, S.S. 1976. Landforms of British Columbia: a physiographic outline. B.C. Dep. Mines Pet. Resources Bull. 48.

Hungr, O., G.C. Morgan, and R. Kellerhals. 1984. Quantitative analyses of debris torrent hazards for design of remedial measures. Canadian Geotechnical Journal. 21(4):663-677.

Krag, R.K., E.A. Sander, and G.V. Wellburn. 1986. A forest engineering analysis of landslides in logged areas on the Queen Charlotte Islands, British Columbia. B.C. Min. For. Lands. Land Manage. Rep. 43. 138 p.

Lewis, T. 1982. The ecosystems of Tree Farm Licence 24, Queen Charlotte Islands, B.C. Report to Western Forest Products, Vancouver, B.C. 189 p.

Mark, D.M. and M. Church. 1977. On the misuse of regression in earth science. Mathematical Geology 9:63-75.

Morrison, P.H. 1975. Ecological and geomorphological consequences of mass movements in the Alder Creek Watershed and implications of forest land management. B.Sc. thesis. Univ. Oreg., Eugene, Oreg.

Nakano, H. 1971. Soil and water conservation functions of forests on mountainous land. Gov. For. Eng. Stn. (Japan). For Influences Dir.

O'Loughlin, C.L. 1972. An investigation of the stability of the steepland forest soils in the Coast Mountains, Southwest British Columbia. Ph.D. thesis. Univ. B.C., Vancouver, B.C.

Poulin, V.A. 1984. A research approach to solving fish/forestry interaction in relation to mass wasting on the Queen Charlotte Islands. B.C. Min. For., Land Manage. Rep. 27. 16 p.

Reneau, S.L. and W.E. Deitrich. 1987. Size and location of colluvial landslides in a steep forested landscape. *In* Erosion and sedimentation in the Pacific Rim. R. Beschta, T. Dunn, C.E. Grant, G.C. Ice, and F.J. Swanson (editors). IAHS Publ. No. 165, pp. 39-48.

Rice, R. and N. Pillsbury. 1982. Predicting landslides in clearcut patches. *In* Proc. Exeter. Symp., July 1982. Int. Assoc. Hydrol. Sci. Publ. No. 137.

Rollerson, T.P. 1984. Terrain stability study - TFL 44. Woodland Services Division. MacMillan Bloedel Ltd., Nanaimo, B.C. 86 p. and appendices.

Rollerson, T.P. and M. Sondheim. 1985. Predicting post logging terrain stability: a statistical-geographic approach. Proc. IUFRO Mountain Logging Section and the 6th Pac. NW Skyline Logging Symp. Vancouver, B.C.

Rood, K.M. 1984. An aerial photograph inventory of the frequency and yield of mass wasting on the Queen Charlotte Islands, British Columbia. B.C. Min. For., Land Manage. Rep. 34. 55 p.

Schwab, J.W. 1983. Mass wasting October-November 1978 storm, Rennell Sound, Queen Charlotte Islands, British Columbia. B.C. Min. For., Research Note 91. 23 p.

Sidle, R.C., A.J. Pearce, and C.L. O'Loughlin. 1985. Hillslope stability and land use. Water Resource Monogr. 11. Am. Geophysical Union, Washington, D.C. 140 p.

Smith, R.B., P.R. Commander, and M.W. Ryan. 1986. Soils, vegetation and forest growth on landslides and surrounding logged and old-growth areas on the Queen Charlotte Islands. B.C. Min. For., Land Manage. Rep. 41. 95 p.

Sutherland Brown, A. 1968. Geology of the Queen Charlotte Islands. B.C. Dep. Mines Pet. Resources Bull. 54. 226 p.

Swanston, D.N. 1969. Mass wasting in coastal Alaska. U.S. Dep. Agric. For. Serv., Res. Pap. PNW-83. 15 p.

_____ . 1974. The forest ecosystem of southeast Alaska. Chap. 5 Soil mass movement. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. PNW-17. 22 p.

_____ . 1976. Erosional processes and control methods in North America. Proc. XVI IUFRO Worlds Congress, Division I: 251-275.

Varnes, D.J. 1978. Slope movement types and processes. *In* Landslides analysis and control. Special Rep. 176, Transport. Research Board, Nat. Acad. Sci., Washington, D.C., pp. 11-33.

Wilford, D. and J. Schwab. 1982. Soil mass movements in the Rennell Sound area, Queen Charlotte Islands, B.C. Proc. Can. Hydrol. Symp., Fredericton, N.B., pp. 521-541.

Yoshinori, T. and K. Osamu. 1984. Vegetative influences on debris slide occurrences on steep slopes in Japan. Symp. on the Effects of Forest Land on Erosion and Slope Stability. Honolulu, Hawaii.

APPENDIX 1. Definition of variables used to describe landslides

VARIABLE CODES AND DEFINITIONS

Table A.1 lists the variable, variable type, and a description for the 27 different variables collected for each failure. Variables are described as interval, ordinal or nominal (Blalock 1972). A more detailed description of the classification procedure for some variables follows.

Landslide Type: This is described in detail in the body of the report.

Failure Descriptors: For estimating volumes and describing slides, failures were subdivided into initiation, transport, and depositional zones (Figure 2). Generally, the initiation zone is an area of complete scour, and typically includes the steepest part of the failure. The transport zone is an area of lower gradient and for debris slides may be an area of deposition and scour. For debris flows, the transport zone is the scoured portion of the channel. The depositional zone occurs where material from the initiation and runout zones is deposited.

In some cases, these zones were distinct; in others they were not. Often the division between the initiation and runout zone is based simply on changes of slope along the failure. For smaller features these zones are often indistinguishable and measurements were often recorded as belonging to the initiation zone.

Initiation Zone Descriptors:

Initiation Slope: This was calculated from the difference in elevation at the top and bottom of the initiation zone and the projected length of that zone. For large failures, the maximum slope in the zone was also recorded if different from the average.

Initiation Length: This is the horizontal or plan length of the initiation zone in metres. The slope length was the plan length multiplied by the secant of the initiation slope.

Initiation Width: This is the average horizontal or plan width of the initiation zone in metres.

Initiation Depth: After Smith *et al.* (1983). From measurements on 45 failures, the average depth of soil removal from the initiation zone was found to be 0.44 m. As this depth corresponded roughly to the vertical resolution of the stereoplotter, it was not possible to directly measure differences in depth between different failures. However, the general appearance of the failures occasionally indicated depths different than average and, as a result, depths were estimated as 0.25, 0.50, 1.0, or 2.0. Almost all initiation depths were assumed to be 0.5.

Field investigations by the author in January and May 1983, and by the Forest Engineering Research Institute of Canada (FERIC) in the summer of 1983, were used to adjust some initial results.

Transport Zone Descriptors:

Transport Length: This is the plan length of the runout zone in metres. In some cases in this study it was not clear how far most of the debris travelled.

Transport Slope: This slope was calculated from the difference in elevation between the bottom of the initiation zone and the top of the depositional zone, and from the runout length. For long runout zones, a minimum slope was sometimes recorded.

Transport Width: This is the plan average width of the runout zone in metres.

Transport Depth: For debris slides the runout zone is an area of mixed scour and deposition. The runout depth was assumed to be equal to one-half the depth in the initiation zone, made up of approximately one-half scour and one-half deposition. For debris flows, the runout depth was calculated from the volume of the flow and the approximate surface area of the zone, or an average value based on other flows was used.

Deposition Zone Descriptors:

Volume of Event: The total volume entering the depositional zone was determined from measuring the volume in the depositional zone (for debris flows) or, more commonly, from combining widths, lengths, and estimated depths of the initiation and runout zones. The volume existing in the initiation zone was estimated as:

$$\text{length} \times \text{width} \times \text{depth} \times 1/\cos 0.$$

The volume contributed by the runout zone was calculated in a similar manner, though the depth used for debris slides was typically one-half the value from the initiation zone, to compensate for the lesser degree of scour.

When the volume of material in the depositional zone was measured, this was used in conjunction with the surface area of the failure to calculate the depths of material yielded by the initiation and runout zones. These calculations were used to estimate the volume of material yielded by events where the depositional area was not clearly visible. Note that estimates of the volume of deposited material included organic debris which, in some cases, can comprise 50% or more of the total debris. This organic component was not included in volume estimates calculated from measurement of the initiation and runout zones.

Volume Entering Streams: Streams were defined as channel reaches with gradients less than 10%. Consequently, the headward extensions of the stream net were referred to as "gullies", and slide material that entered and remained in a gully was not considered to have entered the "stream". Only the coarse fraction of the slide was considered, as information concerning the deposition of fine materials and fluvial reworking of materials could not be obtained from this scale of photography.

Reaches of stream were classified on the basis of gradient into three groups: 0.1-1%, 1-3%, and 3-10%. The classification follows Church (1983) in part, but differs in the gradient classes and in the emphasis on gradient. Gradient, rather than valley flat width or the presence of a footslope, was used to categorize different reaches.

Failure volumes entering streams were estimated to be either $\frac{1}{10}$, $\frac{1}{3}$, $\frac{2}{3}$, or all of the volume of the event.

Environmental Descriptors:

Aspect: The aspect — the direction the initiation zone of the event faces — was recorded to the nearest major compass point.

Slope Form: The shape of the slope in the area near the initiation point of the failure was described. Form was coded as concave, convex, complex, or straight. Complex slope included all types not described by the other three categories. This includes benched slopes and slope segments composed of convex and concave elements.

Slope Position: The position of the initiation zone relative to a local base level was described as upper, mid, or lower. Nearly all gully sidewall failures occurred on lower slopes.

Bedrock Type: Bedrock type follows mapping in Sutherland Brown (1968).

Surficial Materials: Surficial materials at the initiation point were described as till (moraine), colluvium, road fill, and road cut. Till and colluvium were separated on the aerial photographs by gradient and the general appearance of the terrain. Separation is probably poor, and as a result this variable was not analyzed.

Age of Logged Slide: Each slide was assigned the age of the clearcut patch in which it occurred. The age of clearcut patches was taken from logging history maps supplied by the Fish/Forestry Interaction Program.

TABLE A.1. Description and classification of variables collected for each landslide from aerial photographs

Variable	Variable type	Variable description
Landslide Type	nominal	coded as: open slope debris slide gully headwall debris slide gully sidewall debris slide active wall debris slide debris flow
Slide Description		
Initiation Zone		
maximum slope	interval	angle to nearest degree
average slope	interval	angle to nearest degree
length	interval	distance to nearest 5 m
average width	interval	distance to nearest 5 m
average depth	ordinal	coded as 0.25, 0.5, 1.0, or 2.0 m
Runout Zone		
maximum slope	interval	angle to nearest degree
average slope	interval	angle to nearest degree
length	interval	distance to nearest 5 m
average width	interval	distance to nearest 5 m
average depth	ordinal	coded as 0.15, 0.25, 0.5, or 1.0 m
Depositional Zone		
volume of event	interval	volume to nearest 10 m^3
where volume deposited	nominal	coded as: stream gully slope forest footslope valley flat fan road
does any enter stream?	nominal	coded as: yes no moved by debris flow
% volume entering stream	ordinal	coded as: 10% of volume 33% of volume 67% of volume 100% of volume
reach type	nominal	coded as: I - 3-10% gradient II - 1-3% gradient III - 0.1-1% gradient
length of stream affected	interval	distance to nearest 10 m
Environmental Description		
location of initiation	nominal	coded as: open slope forested gully forested open slope clearcut gully clearcut road cut boundary
aspect	ordinal	coded as: N, NE, E, SE, S, SW, W, NW
slope form	nominal	coded as: concave convex complex straight
slope position	ordinal	coded as: top middle bottom
elevation	interval	elevation to nearest 50 m

TABLE A.1. Continued

Variable	Variable Type	Variable description
Environmental Description		
bedrock type	nominal	coded as: Masset Yakoun Longarm Honna Harda Post Tectonic Pluton Karmutsen Kunga Skidegate
surficial materials at initiation point	nominal	coded as: fill colluvium road fill road cut
age of logged slides	interval	age of logging in years relative to photography
age of forested slides (where determined from aerial photographs)	ordinal	coded as: 0-10 yr 10-20 20-30 30-40
drainage basin	nominal	coded to correspond with the 27 basins mentioned in the previous study
vegetation on slides	nominal	coded as: base sparse shrubs less than 2 m less than 40% cover: 2-5 m 40% cover on transport zone trees: 5-15 m trees: 15-25 m